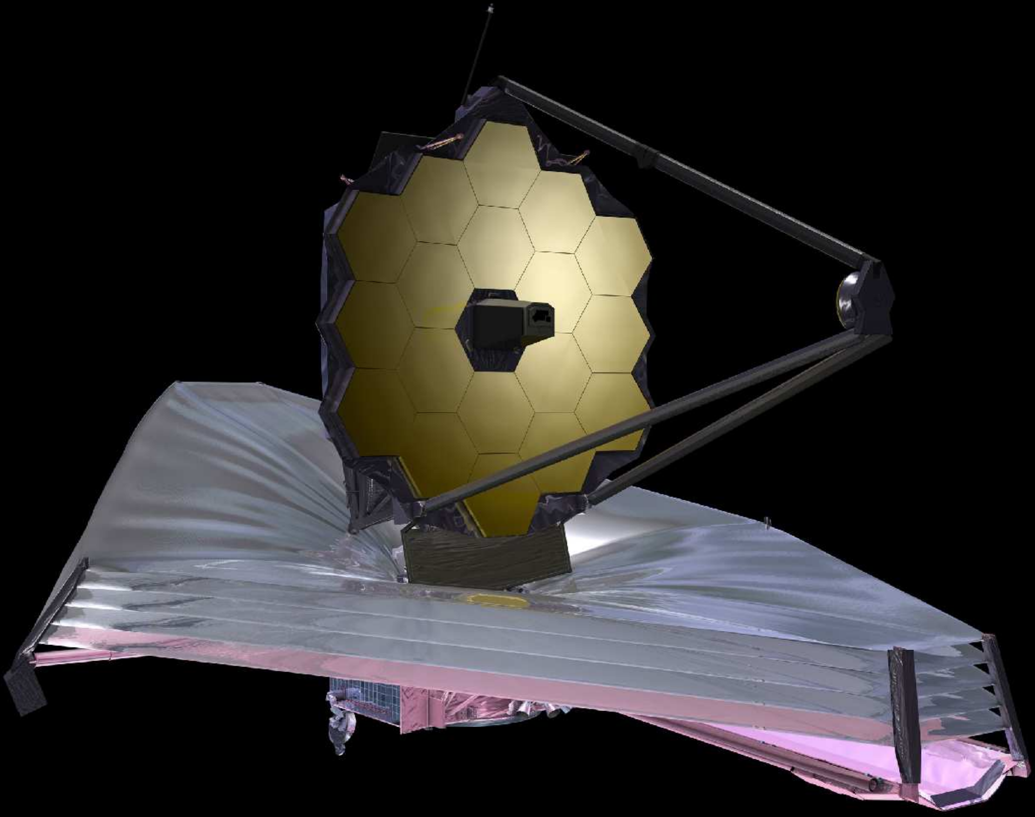
How will JWST measure First Light, Galaxy Assembly & Supermassive Blackhole Growth: New Frontier after HST

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

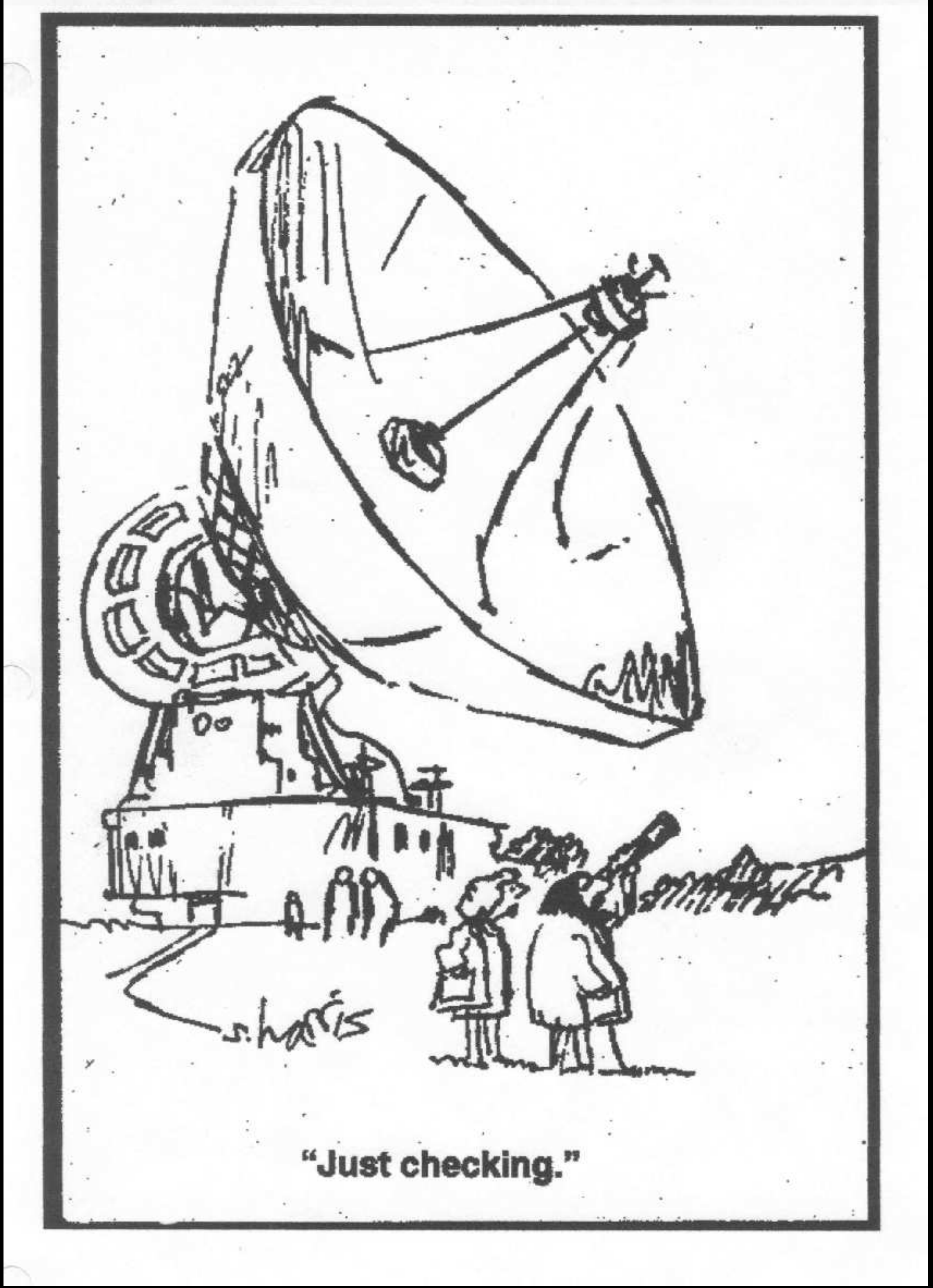
Collaborators: S. Cohen, L. Jiang, R. Jansen (ASU), C. Conselice (UK), S. Driver (OZ), & H. Yan (U-MO)

(Ex) ASU Grads: N. Hathi, H. Kim, M. Mechtley, R. Ryan, M. Rutkowski, B. Smith, & A. Straughn



Colloquium at the Australia Telescope National Facility, CSIRO, Epping, NSW, Australia;

Wednesday, July 31, 2013. All presented materials are ITAR-cleared.



HST and JWST changed the career of this radio astronomer ...

Outline

- (1) Recent key aspects of the Hubble Space Telescope (HST) project.

- (2) Measuring Galaxy Assembly and Supermassive Black-Hole Growth: including first WFC3 z$\simeq$6 QSO host galaxy detection this month ...

- (3) Brief Update on the James Webb Space Telescope (JWST)?

- (4) How can JWST measure the Epochs of First Light & Galaxy Assembly, and Supermassive Black-Hole Growth?

- (5) Summary and Conclusions.

[• (6) How can JWST measure Star-formation & Earth-like exoplanets?]

Sponsored by NASA/HST & JWST

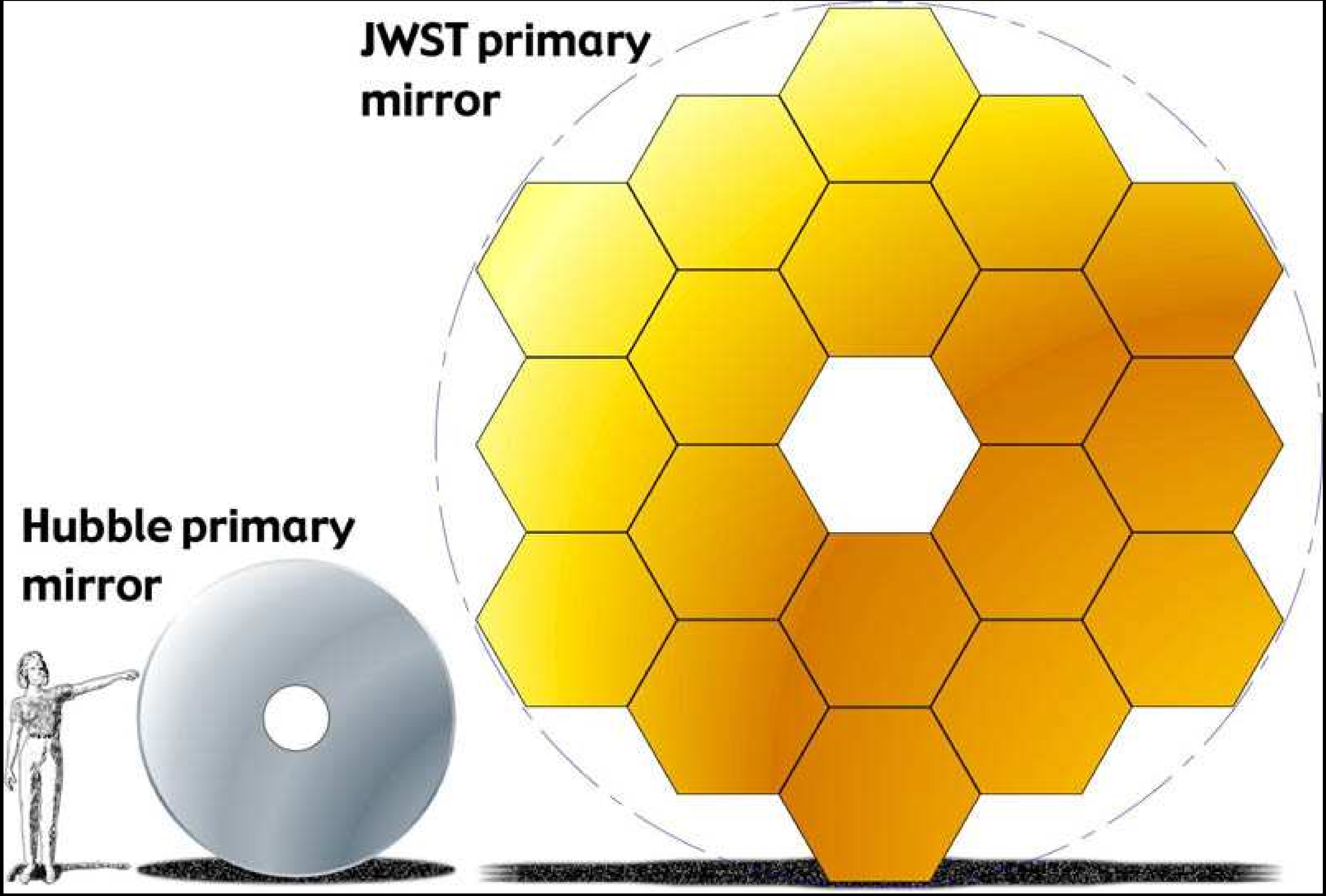
ASU Arizona State University

Edwin P. Hubble (1889–1953) — Carnegie astronomer

James E. Webb (1906–1992) — Second NASA Administrator

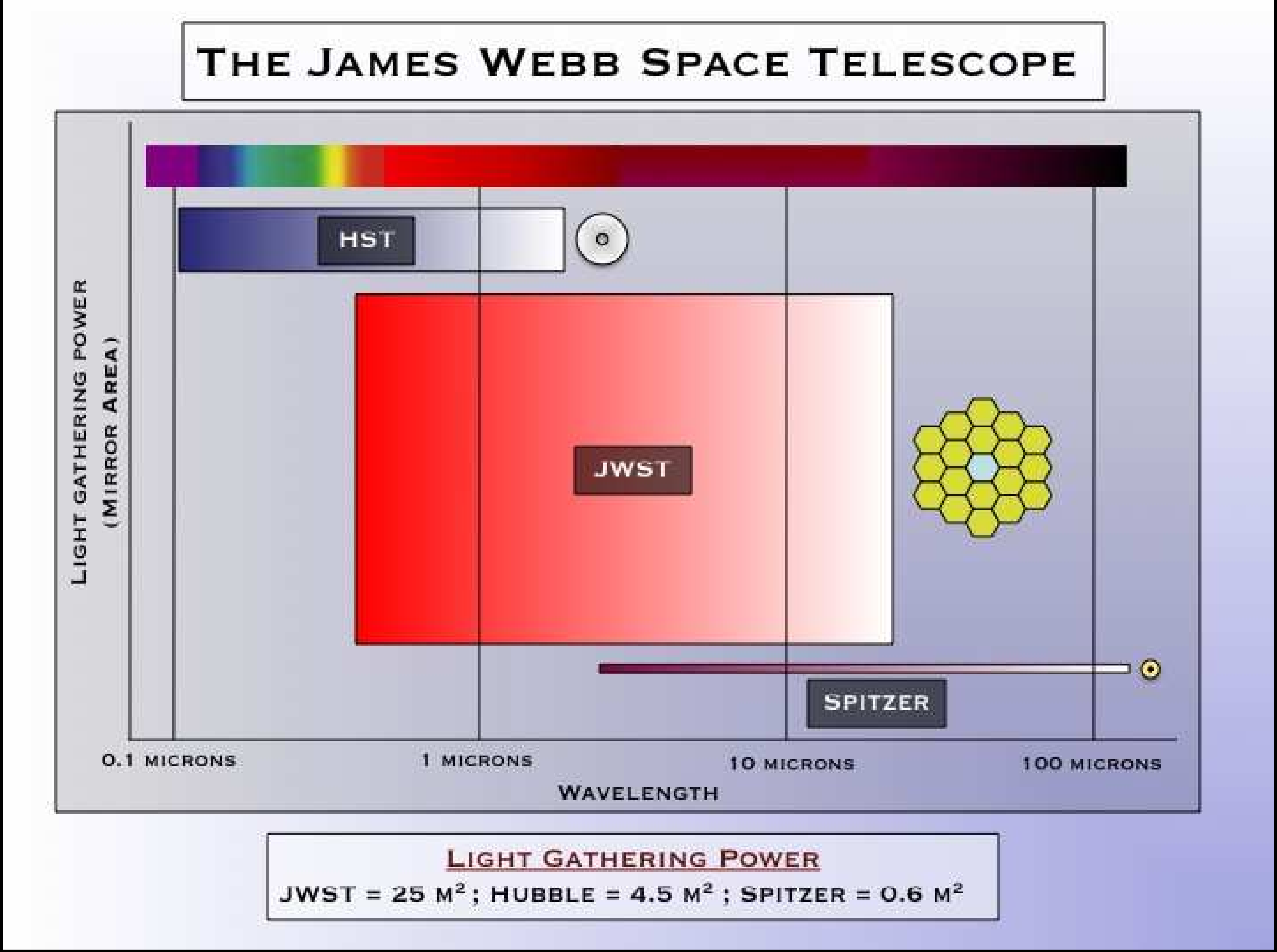
Hubble: Concept in 1970's; Made in 1980's; Operational 1990–$\gtrsim$2014.

JWST: The infrared sequel to Hubble from 2018–2023 (–2029?).



JWST ≃2.5× larger than Hubble, so at ∼2.5× larger wavelengths:

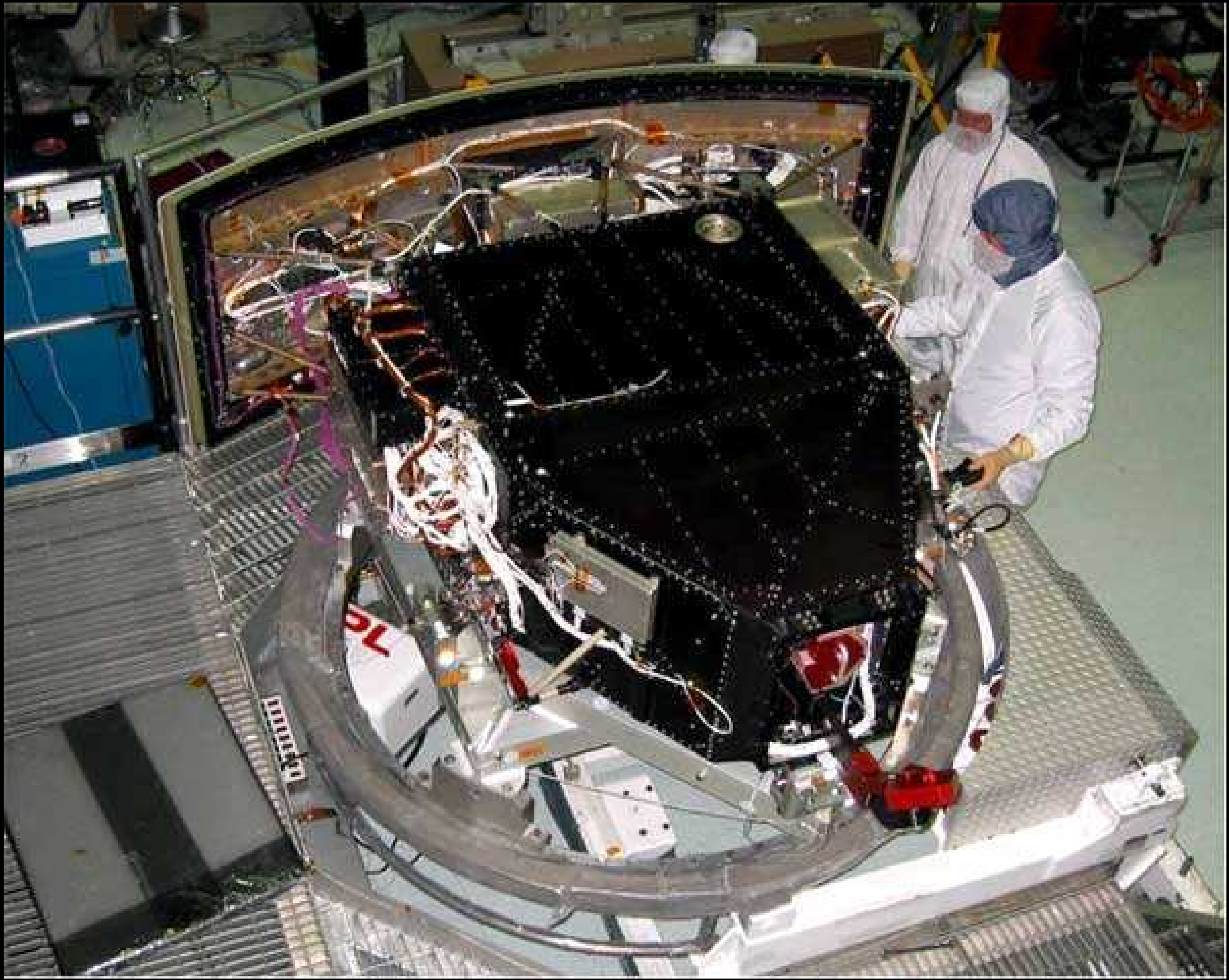
JWST has the same resolution in the near-IR as Hubble in the optical.



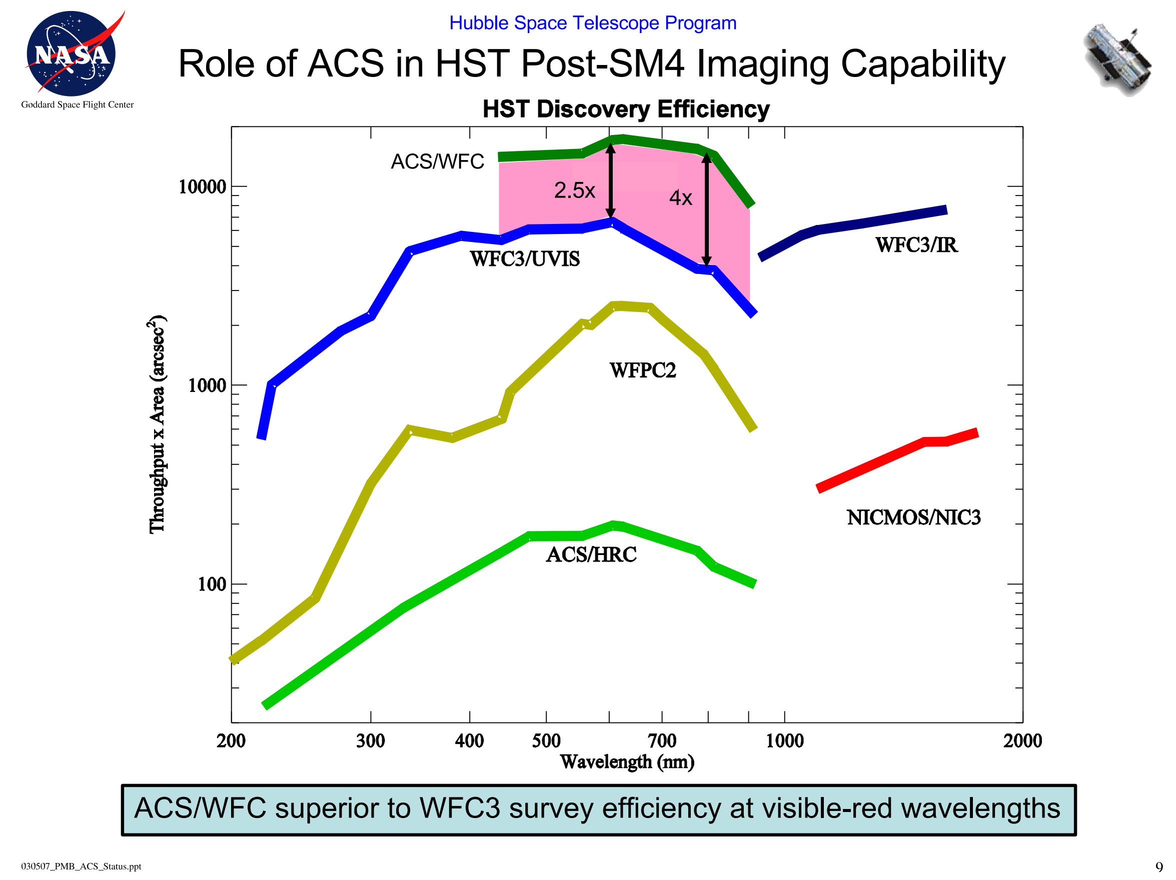
JWST is the perfect near–mid-IR sequel to HST and Spitzer:

- Vastly larger $A(\times\Omega)$ than HST in UV-optical and Spitzer in mid-IR.

(1) WFC3: Hubble's new Panchromatic High-Throughput Camera



HST WFC3 and its IR channel: a critical pathfinder for JWST science.


Hubble Space Telescope Program

Role of ACS in HST Post-SM4 Imaging Capability

ACS/WFC superior to WFC3 survey efficiency at visible-red wavelengths

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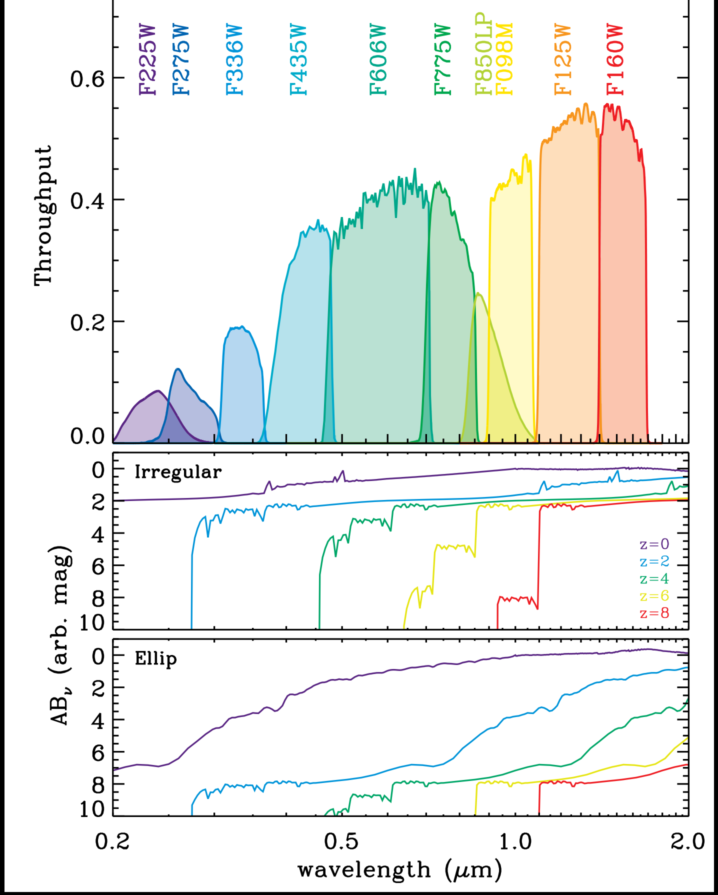


WFC3/UVIS channel unprecedented UV–blue throughput & areal coverage:

- QE$\gtrsim$70%, 4k$\times$4k array of $0''\!.04$ pixel, FOV $\simeq 2'\!.67 \times 2'\!.67$.

WFC3/IR channel unprecedented near–IR throughput & areal coverage:

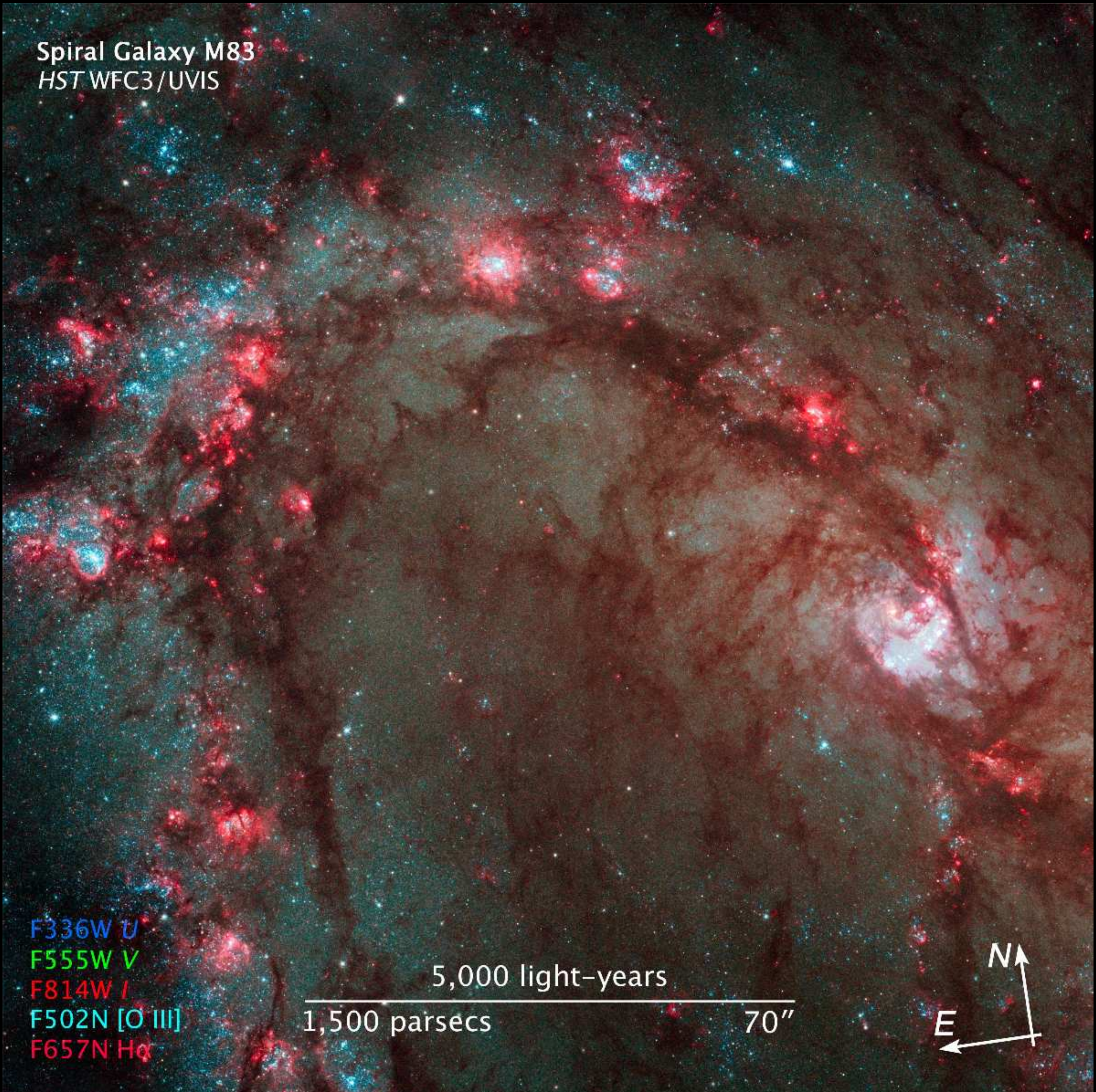
- QE$\gtrsim$70%, 1k$\times$1k array of $0''\!.13$ pixel, FOV $\simeq 2'\!.25 \times 2'\!.25$.

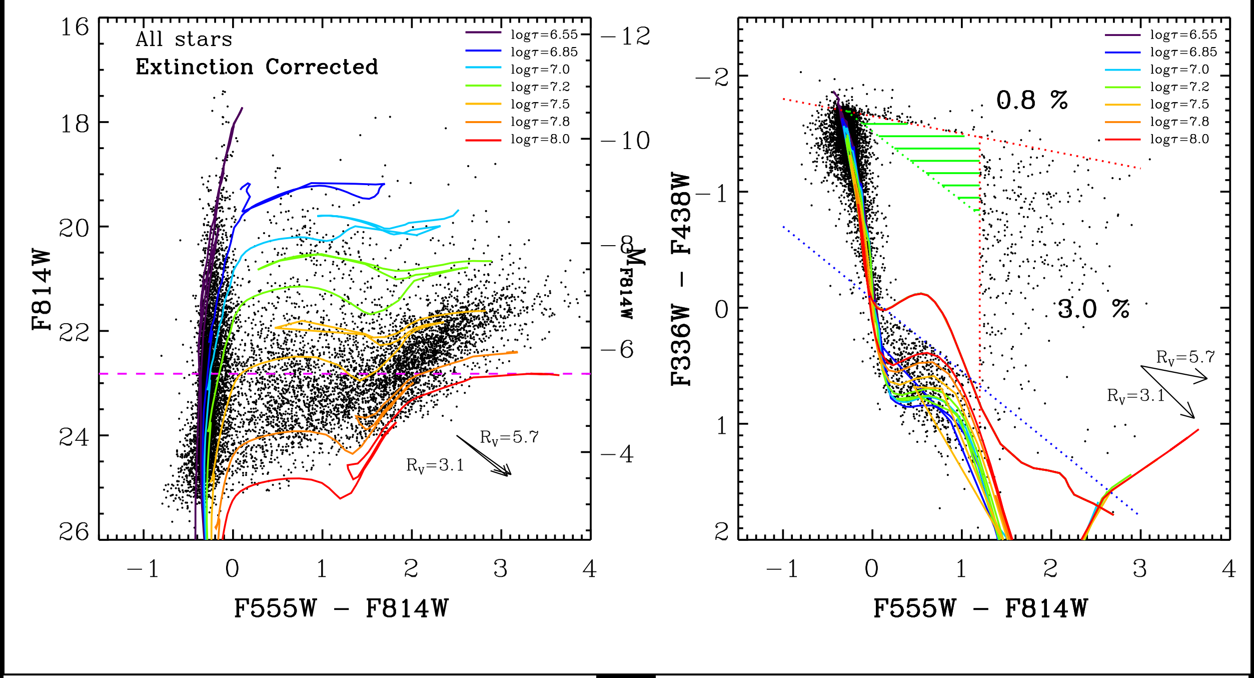
$\Rightarrow$ WFC3 opened major new parameter space for astrophysics in 2009:

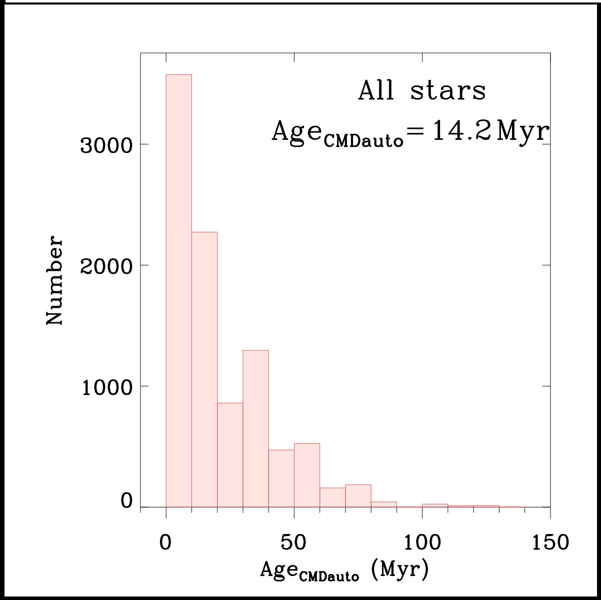
WFC3 filters designed for star-formation and galaxy assembly at z$\simeq$1–8.

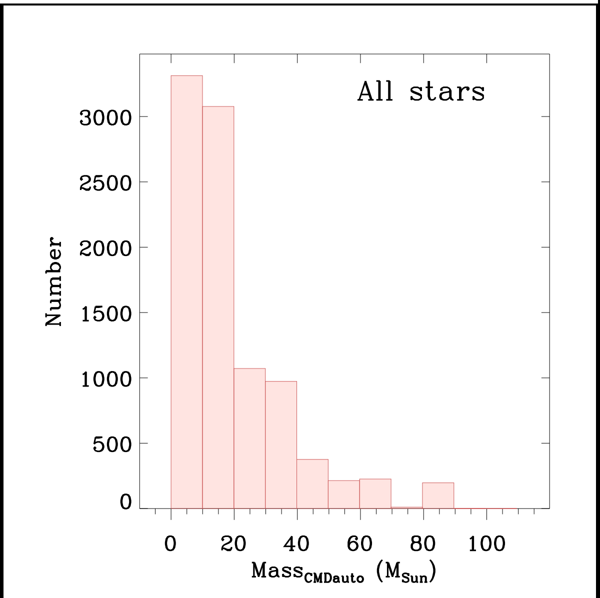
- HST WFC3 and its IR channel a critical pathfinder for JWST science.

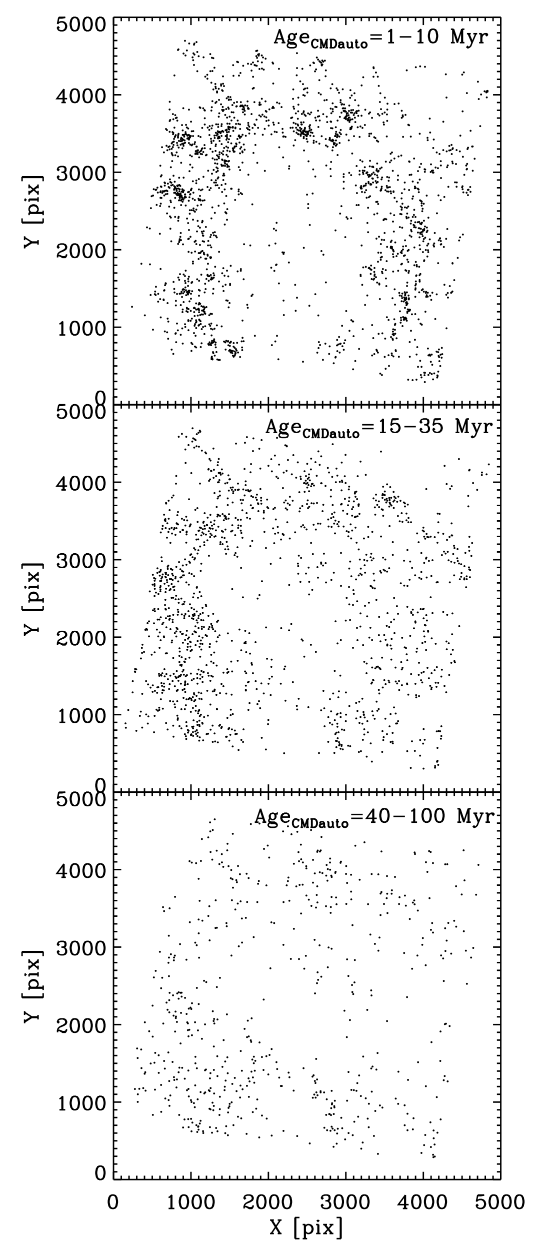
(2) Measuring (Nearby) Galaxy Assembly and Supermassive Black-Hole Growth.









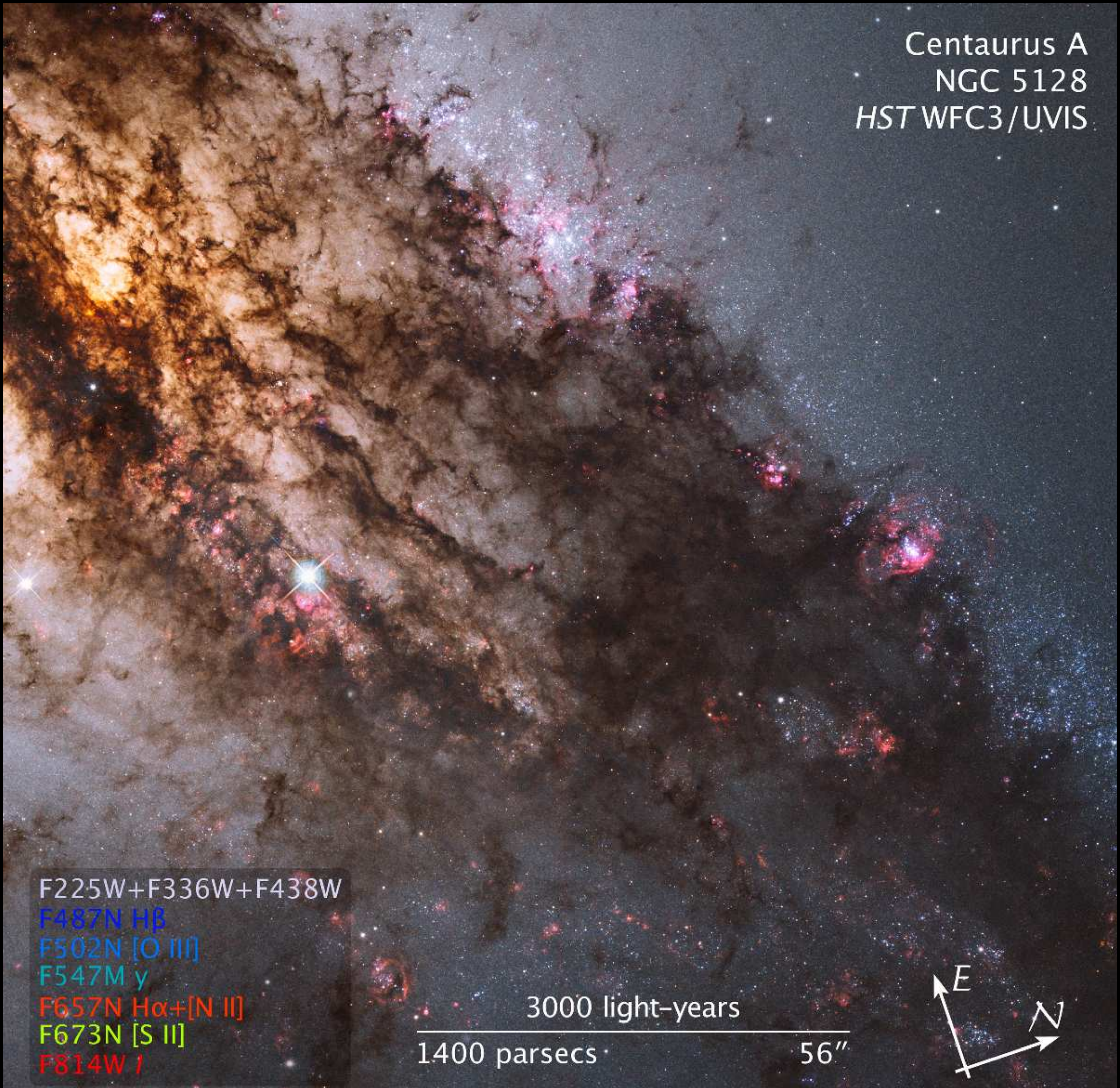


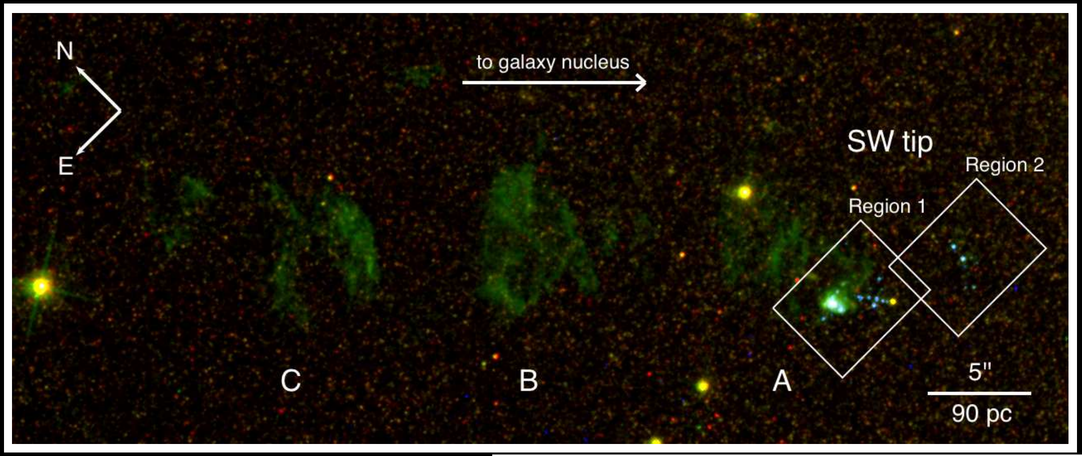
Well determined dust-corrected ages for stars in M83, with formation and dissipation along/across spiral arms (Hwihyun Kim et al. 2012, ApJS).

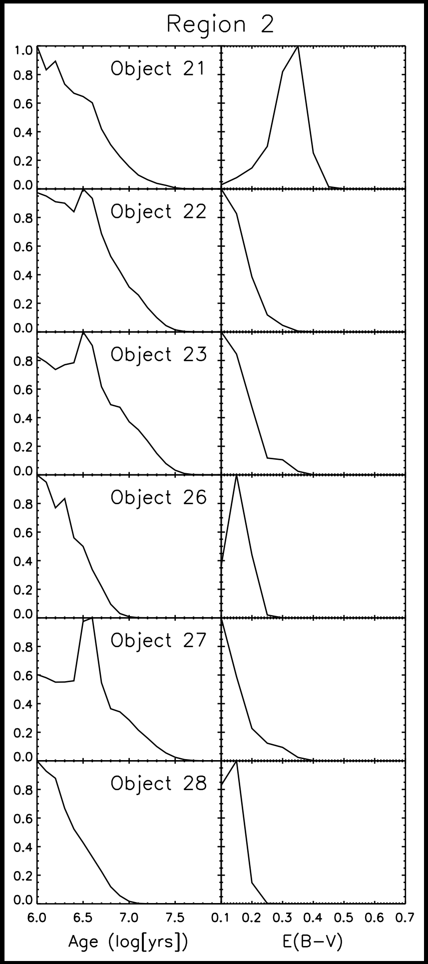
JWST can do this in much dustier environments and for older stellar populations. But must do all we can with HST in UV–blue before JWST flies!

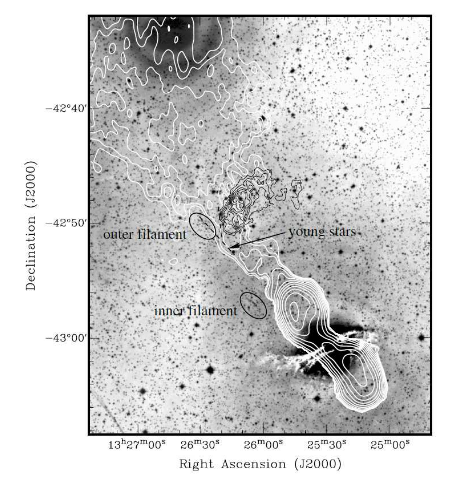
“For God’s sake, Edwards. Put the laser pointer away.”

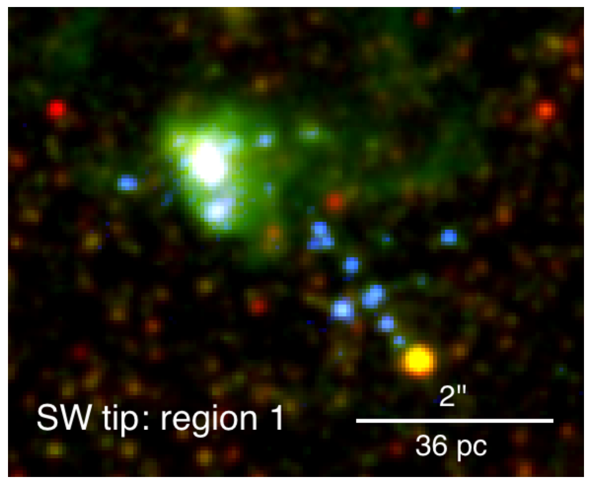
The danger of having Quasar-like devices too close to home ...


Centaurus A
NGC 5128
HST WFC3/UVIS
F225W+F336W+F438W
F487N Hβ
F502N [O III]
F547M y
F657N Hα+[N II]
F673N [S II]
F814W *I*
3000 light-years
1400 parsecs
56″
E
N









[Left] CSIRO/ATNF 1.4 GHz image of Cen A (Feain, Cornwell & Ekers (2009).

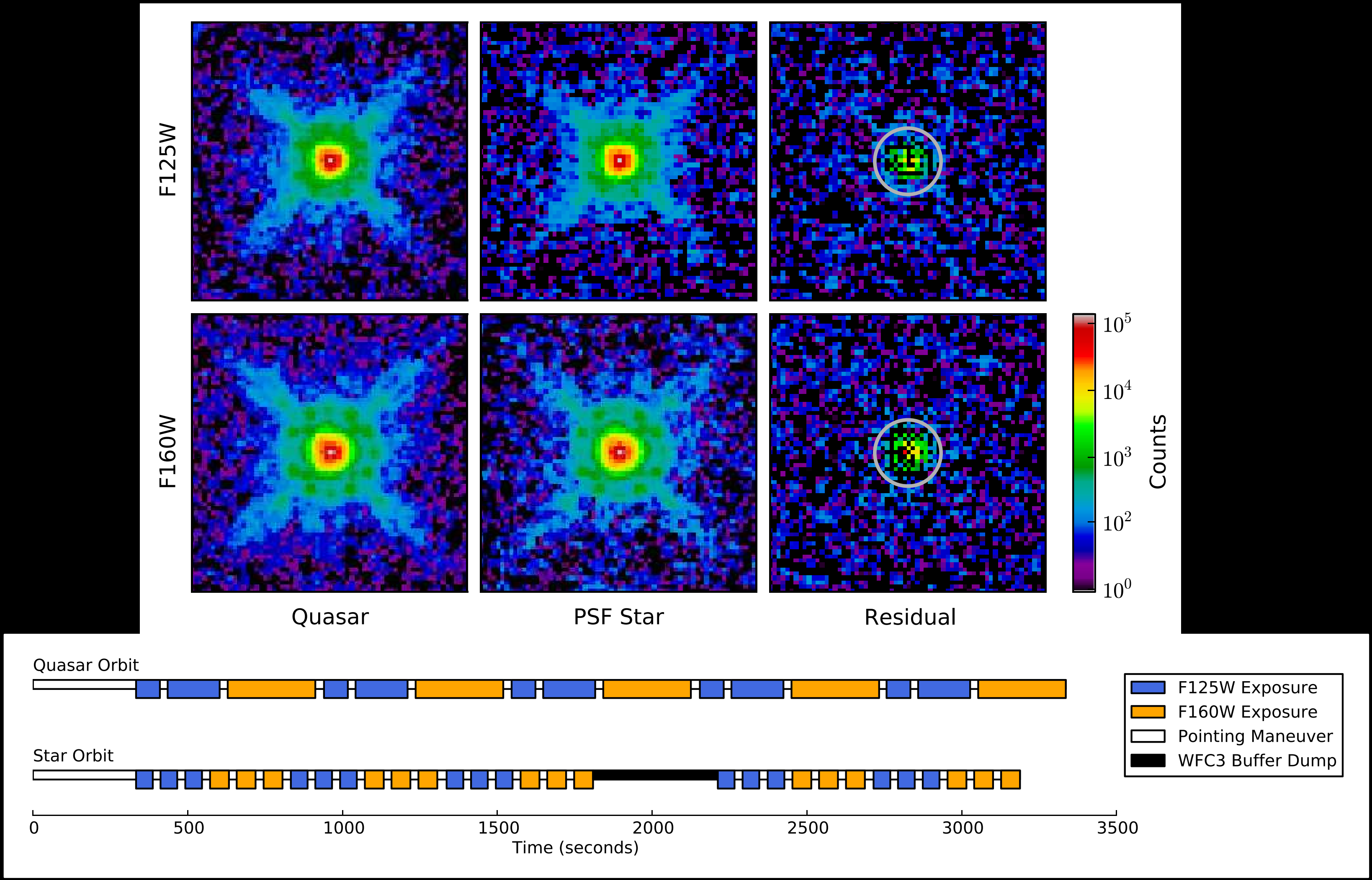
Fermi GeV source (Yang^{+} 12); & Auger UHE Cosmic Rays (Abreu^{+} 2010).

[Middle] SF in Cent A jet's wake (Crockett^{+} 2012, MNRAS, 421, 1602).

[Right] Well determined ages for young (∼2 Myr) stars near Cen A's jet.

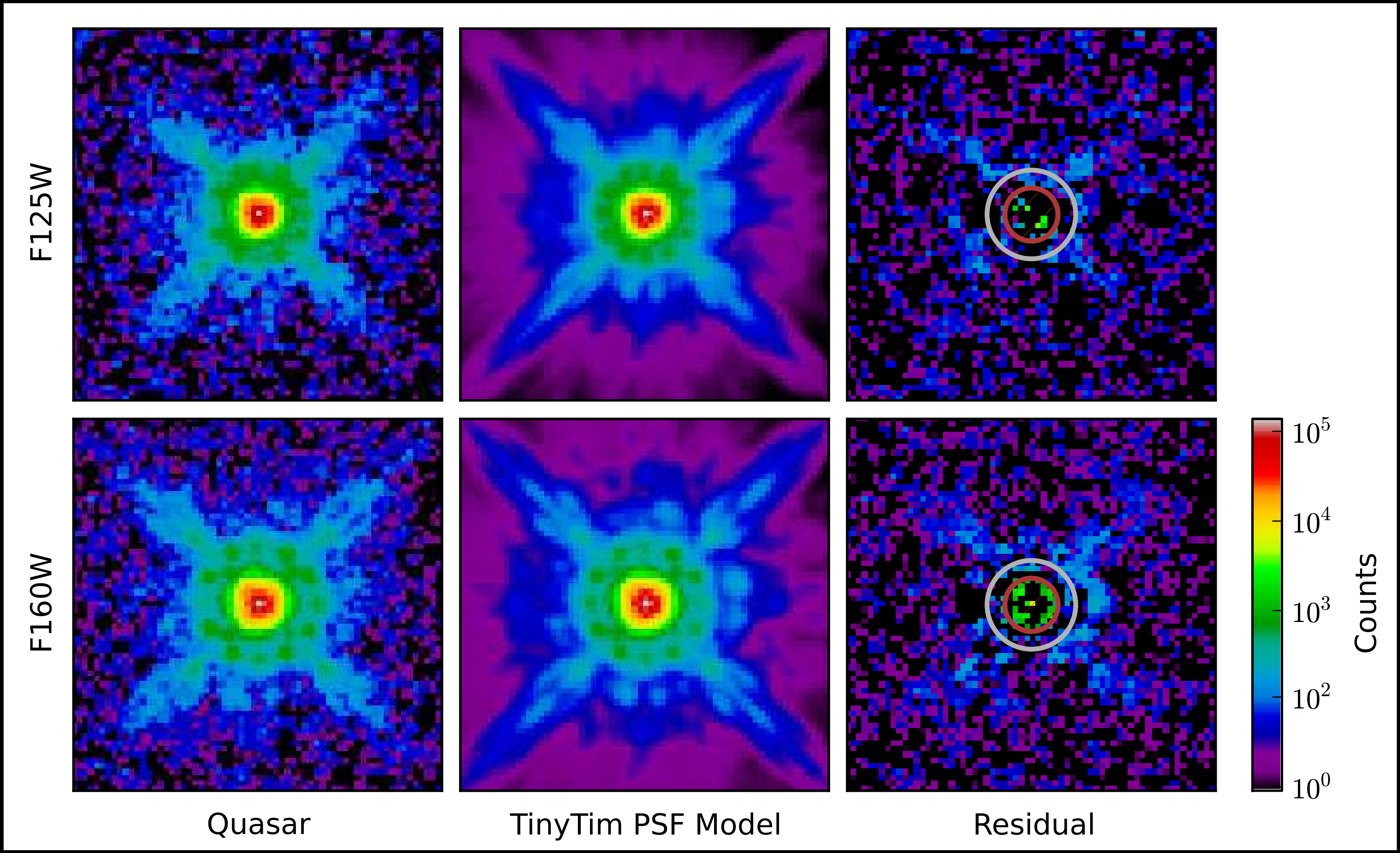
- JWST will trace older stellar pops and SF in much dustier environments.
- We must do all we can with HST in the UV–blue before JWST flies.

(2) HST WFC3 observations of QSO host galaxies at $z \simeq 6$ (age $\lesssim 1$ Gyr)



- Careful contemporaneous orbital PSF-star subtraction: Removes most of "OTA spacecraft breathing" effects (Mechtley ea 2012, ApJL, 756, L38).
- PSF-star (AB$\simeq$15 mag) subtracts z=6.42 QSO (AB$\simeq$18.5) nearly to the noise limit: NO host galaxy detected 100× fainter (AB$\gtrsim$23.5 at $r \gtrsim 0''.3$).

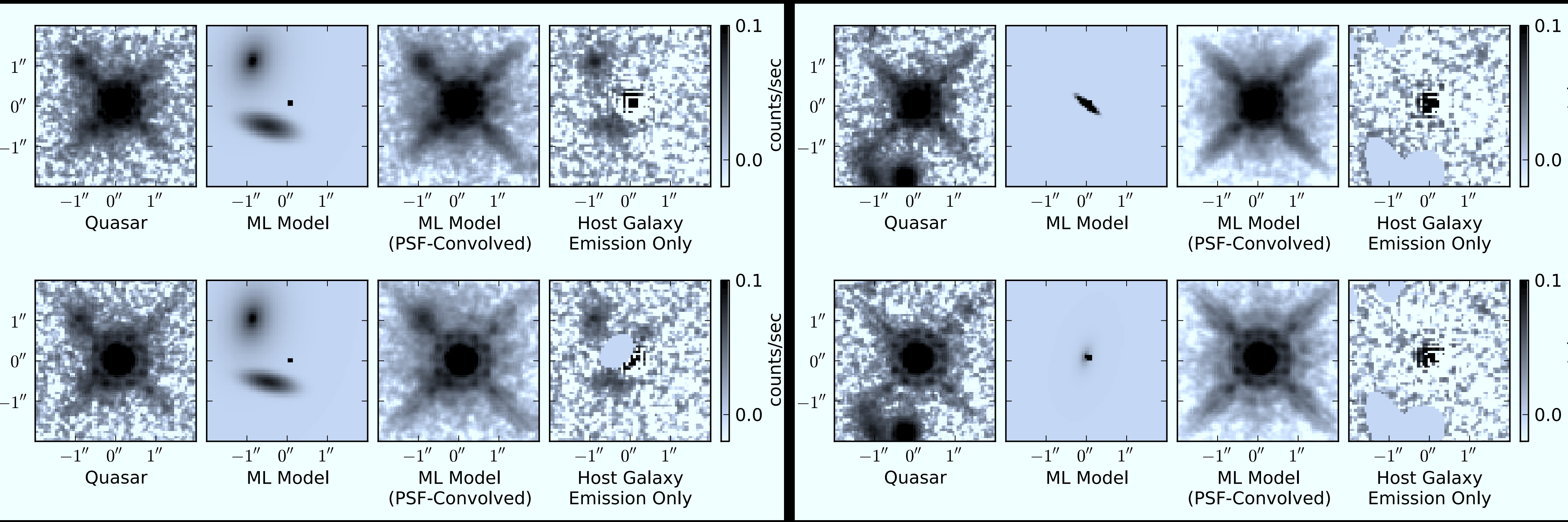
(2) HST WFC3 observations of dusty QSO host galaxies at z$\simeq$6 (age$\lesssim$1 Gyr)



- TinyTim fit of PSF-star + Sersic models QSO nearly to the noise limit: NO z=6.42 host galaxy at AB$\gtrsim$23.5 mag at radius r$\simeq$0.″3–0.″5.

THE most luminous Quasars in the Universe: Are all their host galaxies faint (dusty)? ⇒ Major implications for Galaxy Assembly–SMBH Growth.

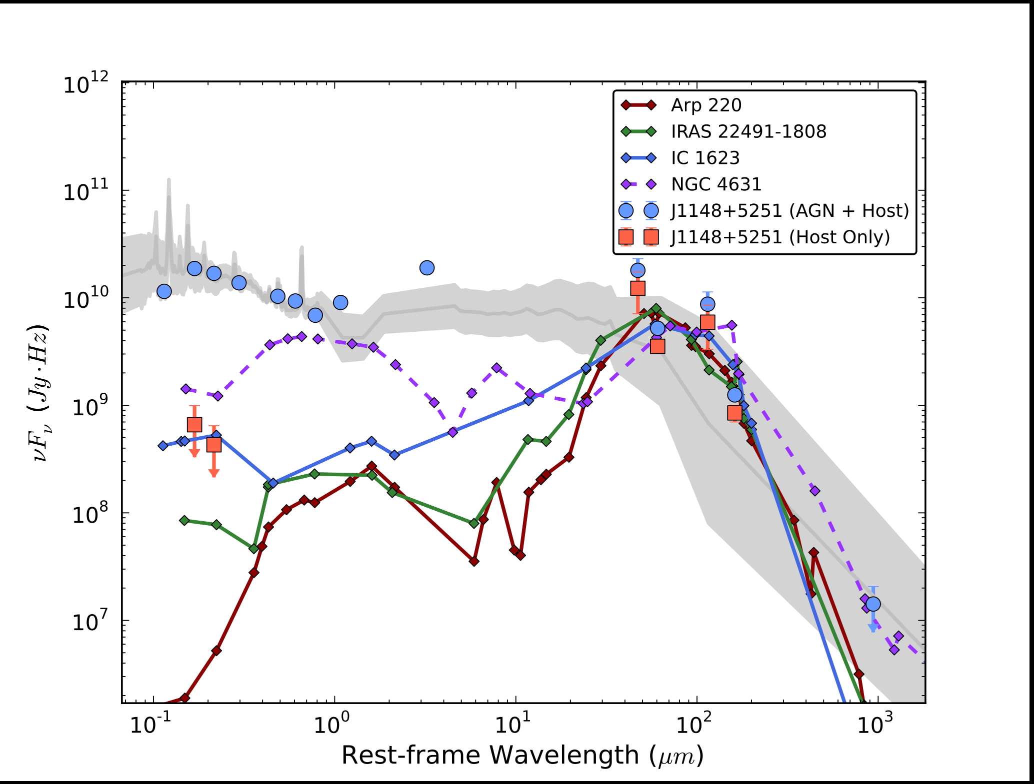
(2) WFC3: First detection of one QSO Host Galaxy at z$\simeq$6 (Giant merger?)

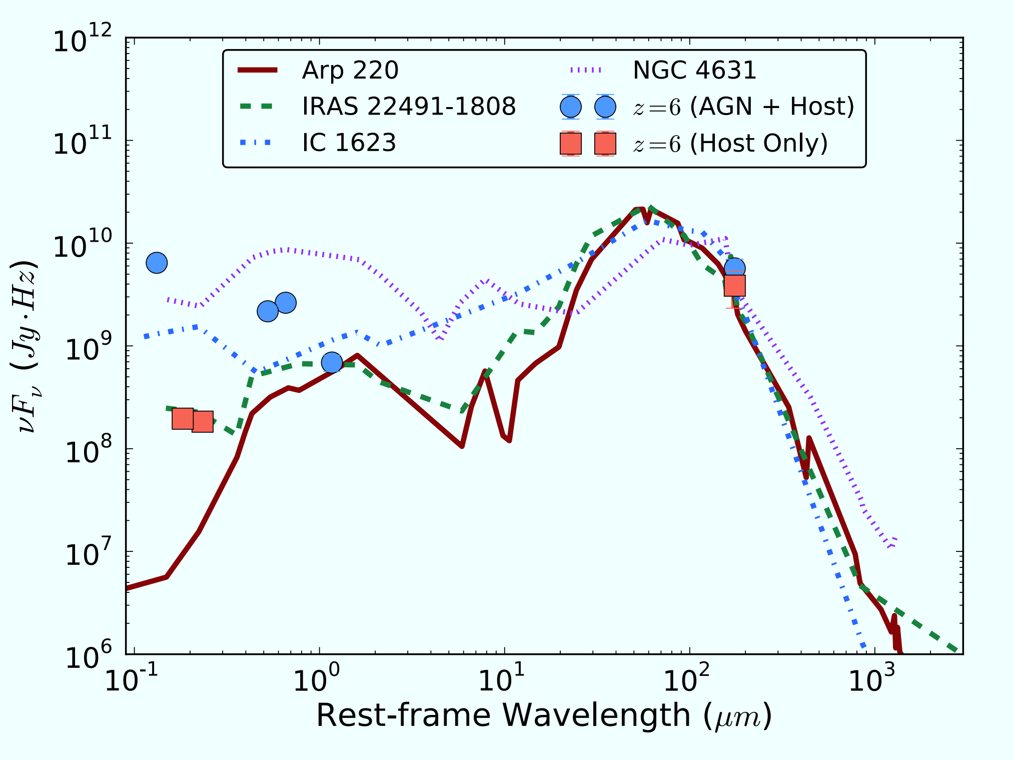


- Monte Carlo Markov-Chain of observed PSF-star + Sersic ML light-profile. Gemini AO data critical for PSF stars (Mechtley^{+} 2013).
- First solid detection out of four z$\simeq$6 QSOs [3 more to be observed].
- One z$\simeq$6 QSO host galaxy: Giant merger morphology + tidal structure??
- Same J+H structure! Blue UV-SED colors: (J–H)$\simeq$0.19, constrains dust.
  - IRAS starburst-like SED from rest-frame UV–far-IR, $A_{FUV}\sim1$ mag.
- $M_{AB}^{host}(z\simeq6)\lesssim-23.0$ mag, i.e., $\sim$2 mag brighter than L*(z$\simeq$6)!

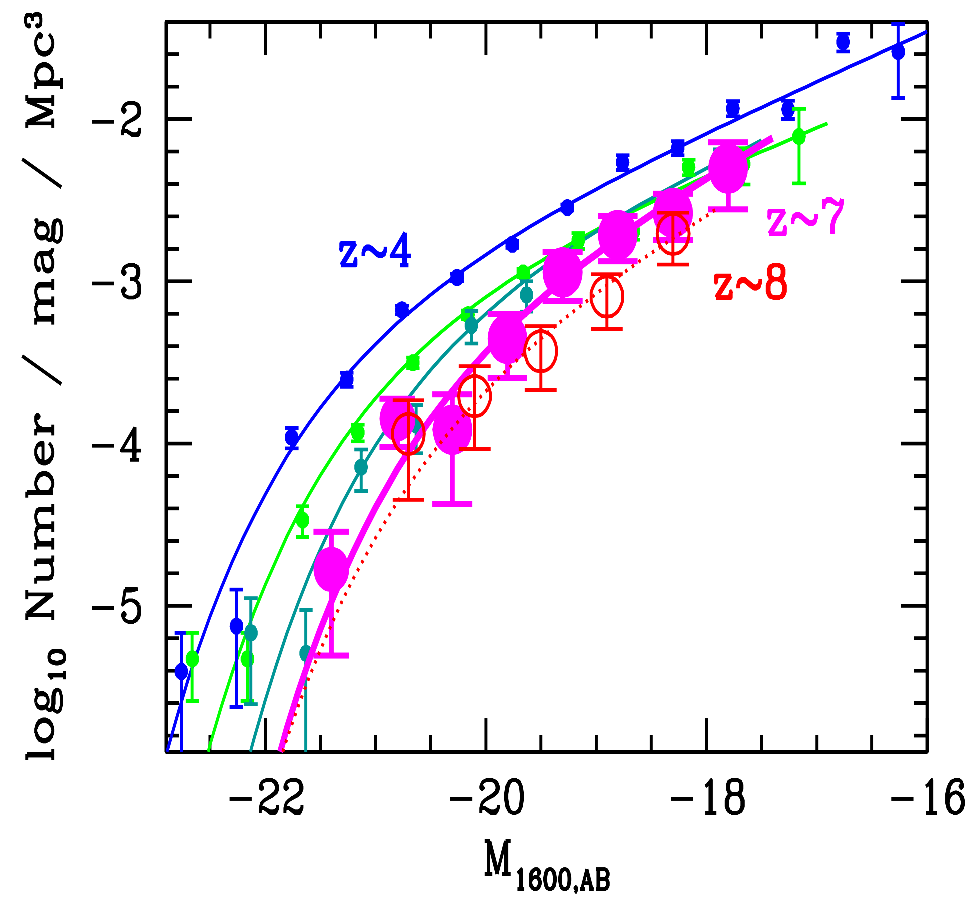
$\Rightarrow$ z$\simeq$6 QSO duty cycle $\lesssim10^{-2}$ ($\lesssim$10 Myrs); 1/4 QSO's close to Magorrian.

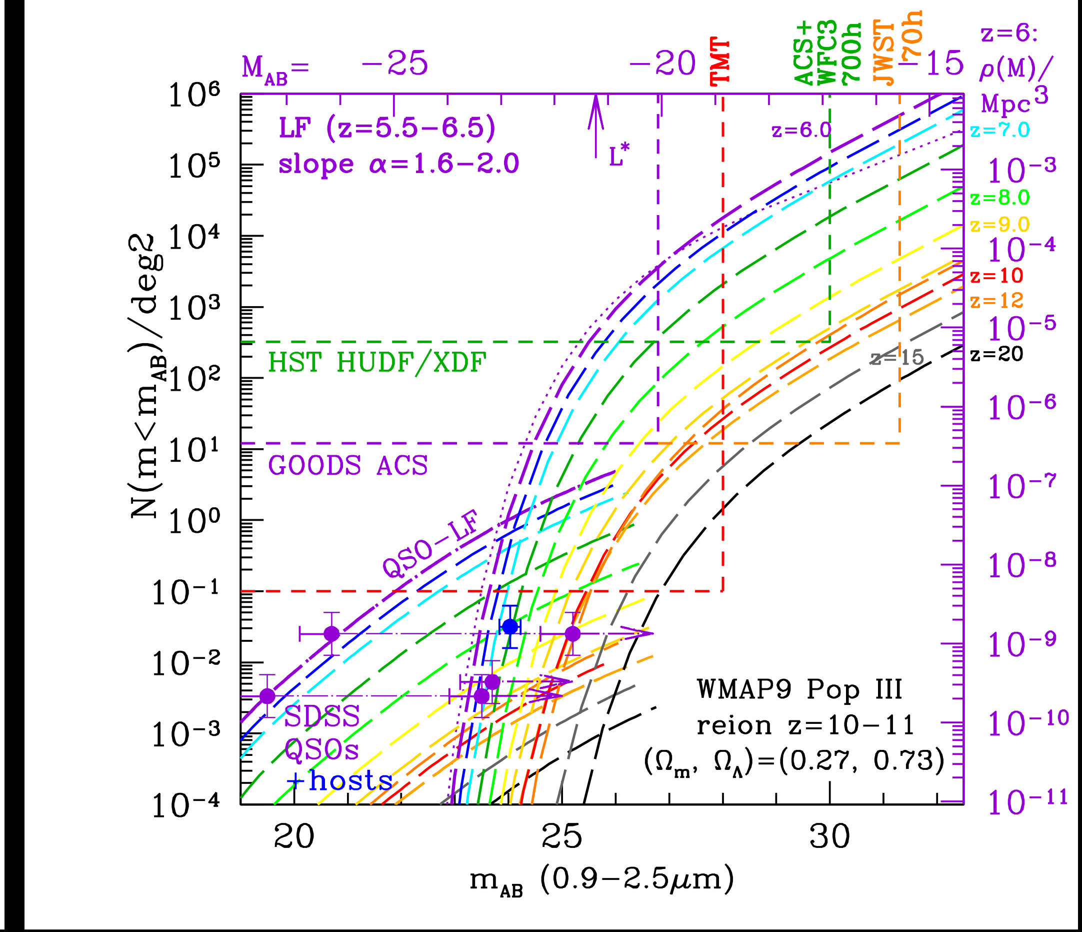
(2) HST WFC3 observations of dusty QSO host galaxies at $z\simeq6$





- Blue dots: $z\simeq6$ QSO SED, Grey: Average radio-quiet SDSS QSO spectrum at $z\gtrsim1$ (normalized at 0.5μ). Red: $z\simeq6$ host galaxy (WFC3+submm).
- Nearby fiducial galaxies (starburst ages$\lesssim$1 Gyr) normalized at 100μm: [LEFT] Rules out $z=6.42$ spiral or bluer host galaxy SEDs for 1148+5251. (U)LIRGs & Arp 220s permitted (Mechtley et al. 2012, ApJL, 756, L38). [RIGHT] Detected QSO host has IRAS starburst-like SED from rest-frame UV–far-IR, A_{FUV}(host)$\sim$1 mag (Mechtley et al. 2013b).
- JWST Coronagraphs can do this 10–100× fainter (& for $z\lesssim20$, $\lambda\lesssim28\mu$m).



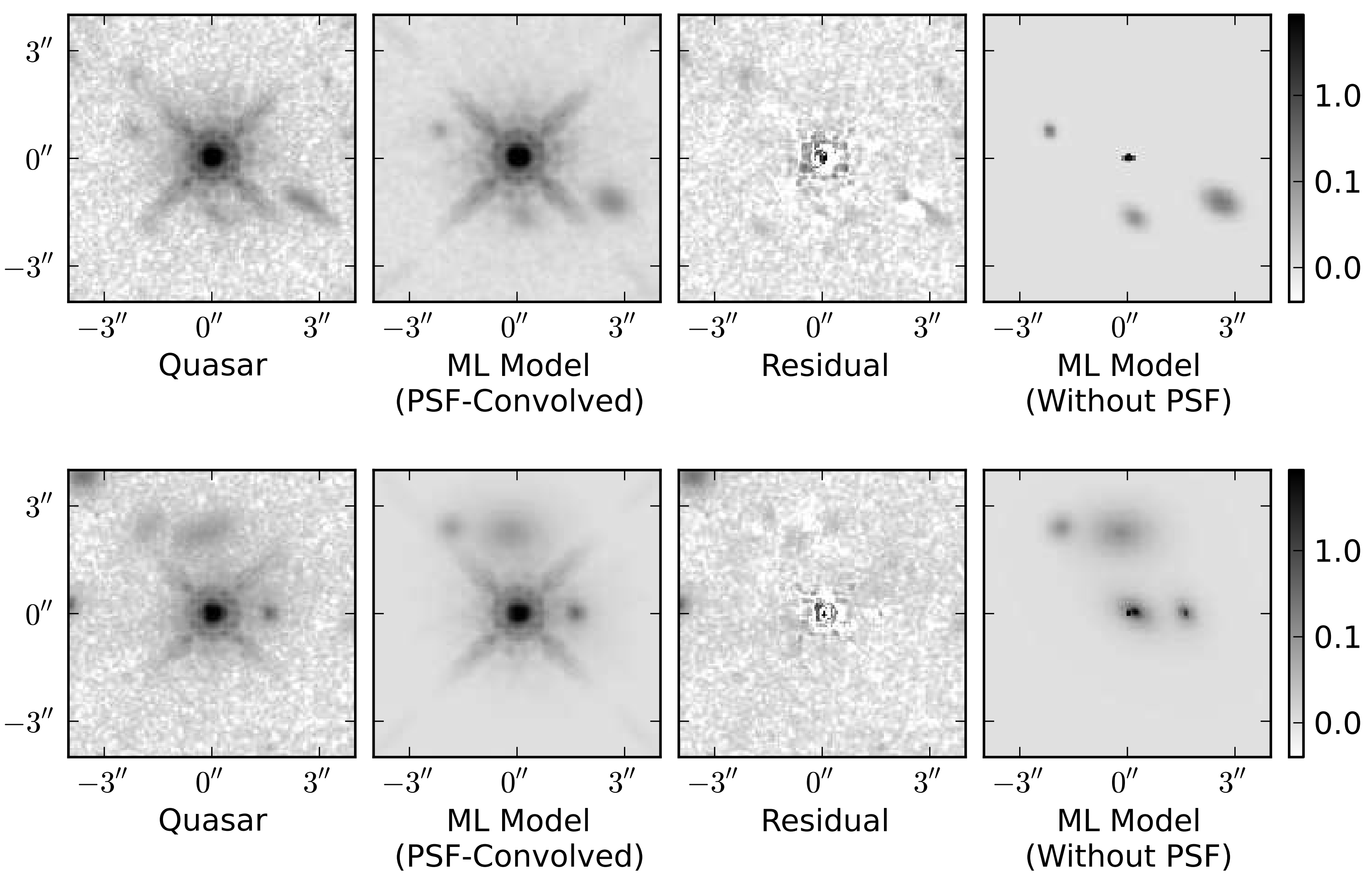


- M_{AB}^{host}(z≃6)≲–23.0 ≃ M*–2 mag at z≃6; 1/4 QSOs @ Magorrian.
  ⇒ z≃6 QSO duty cycle (A_{FUV}≃0⟶1) ≲0.01⟶1.0 (≲10⟶950 Myrs).

- To study co-evolution of SMBH-growth & proto-bulge assembly for z≲10–15 requires new AGN finding techniques for JWST (e.g., Mortlock).

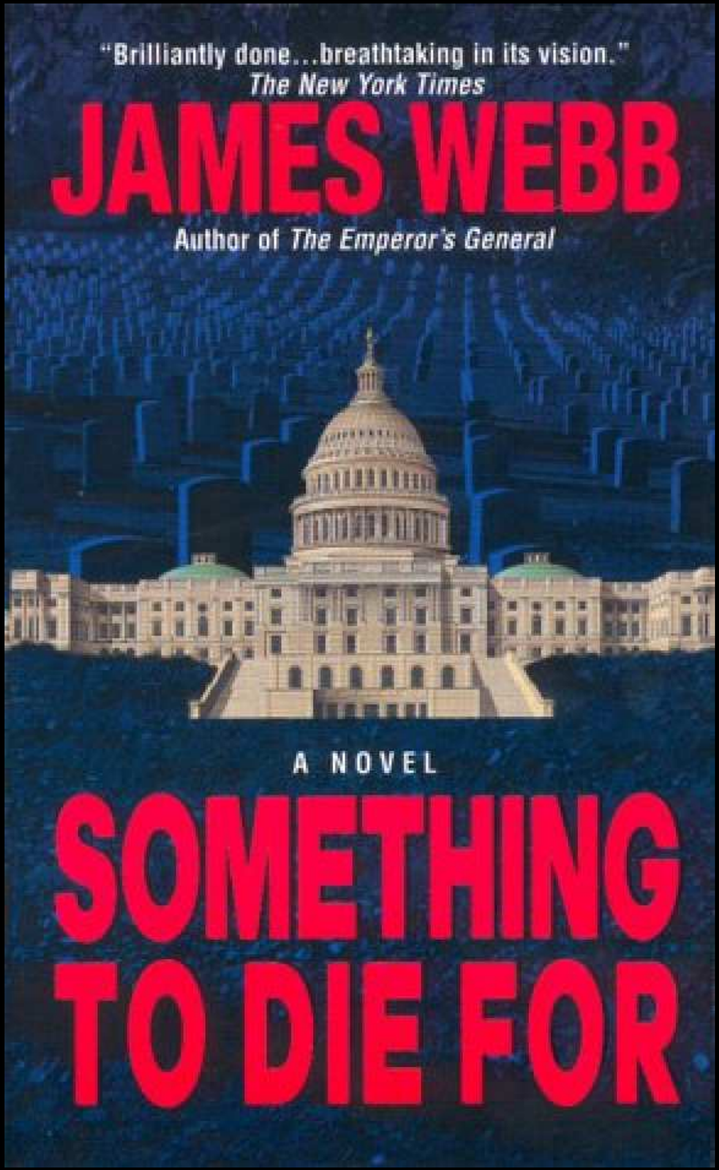
- JWST Coronagraphs can also trace super-massive black-holes as faint quasars in young galaxies: JWST needs 2.0μm diffraction limit for this.

(2) WFC3 observations of QSO host galaxies at z≃2 (evidence for mergers?)



- Monte Carlo Markov-Chain runs of observed PSF-star + Sersic ML light-profile models: merging neighbors (some with tidal tails?; Mechtley, Jahnke, Koekemoer, Windhorst et al. 2013).
- JWST Coronagraphs can do this 10–100× fainter (& for $z \lesssim 20$, $\boldsymbol{\lambda} \lesssim 28\mu$m).

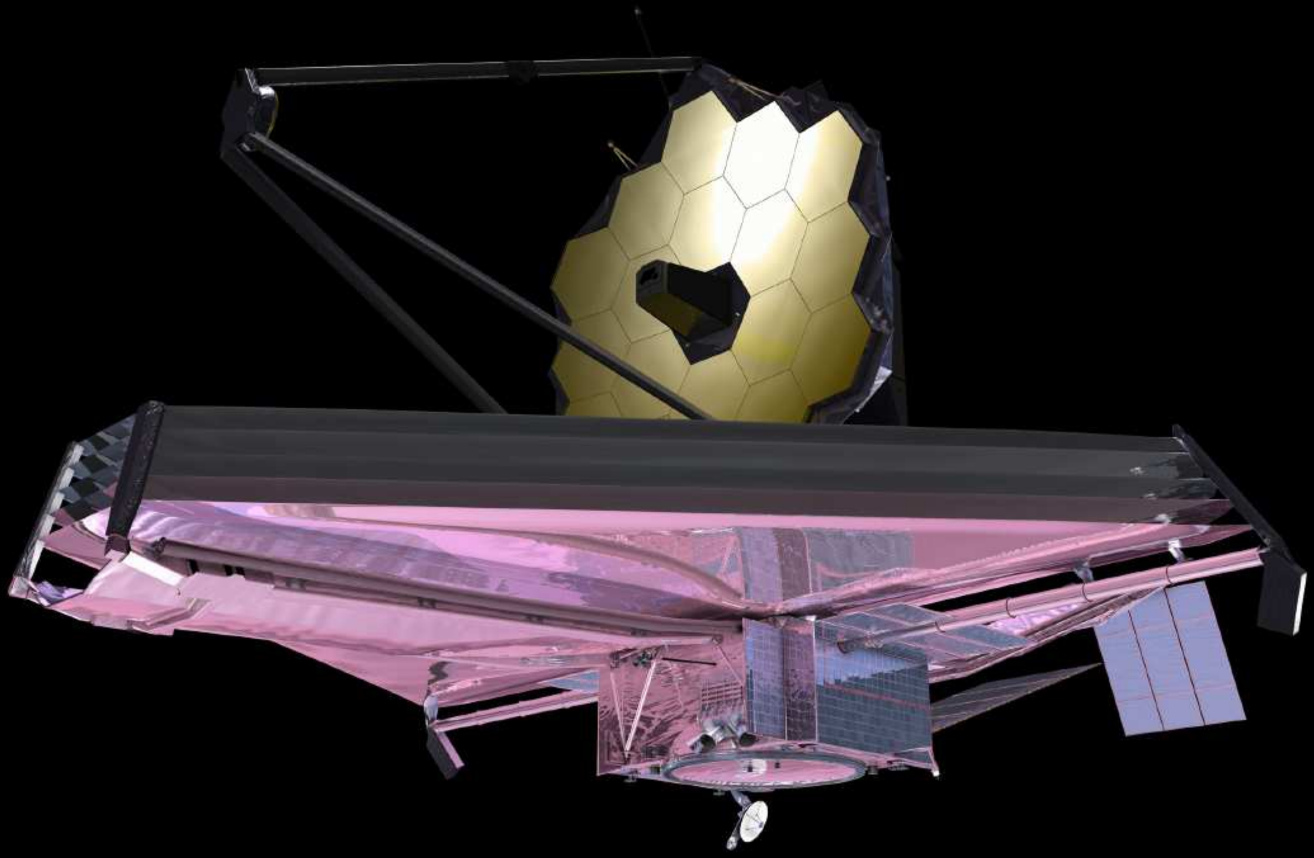
(3) Brief Update of the James Webb Space Telescope (JWST).



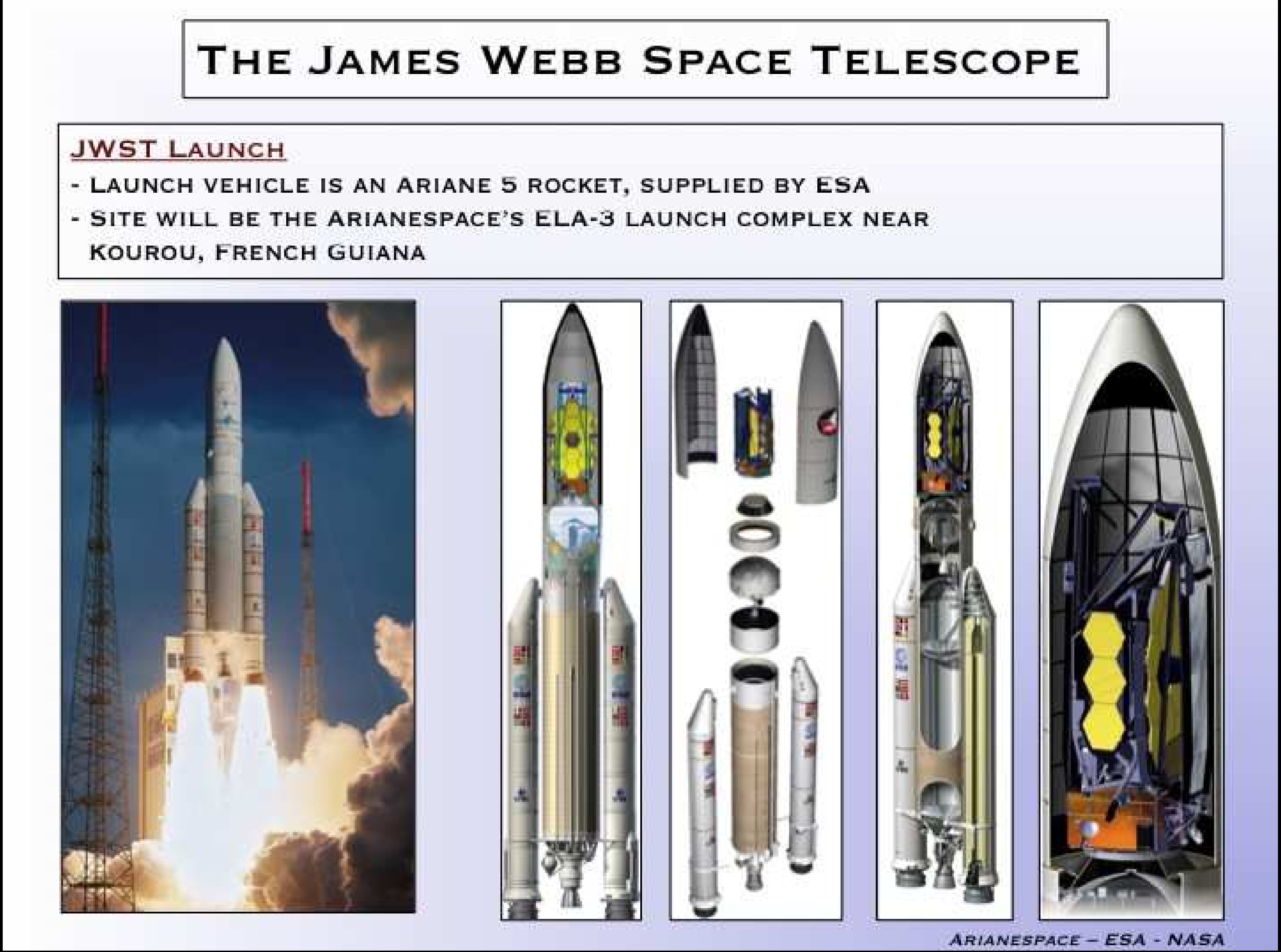
To be used by students & scientists after 2018 … It'll be worth it.

(RIGHT) Life-size JWST prototype on the Capitol Mall, May 2007.

(3) Brief Update of the James Webb Space Telescope



- A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy at 0.6–28 μm wavelength, to be launched in Fall 2018.
- Nested array of sun-shields to keep its ambient temperature at 40 K, allowing faint imaging (AB=31.5 mag) and spectroscopy.



THE JAMES WEBB SPACE TELESCOPE

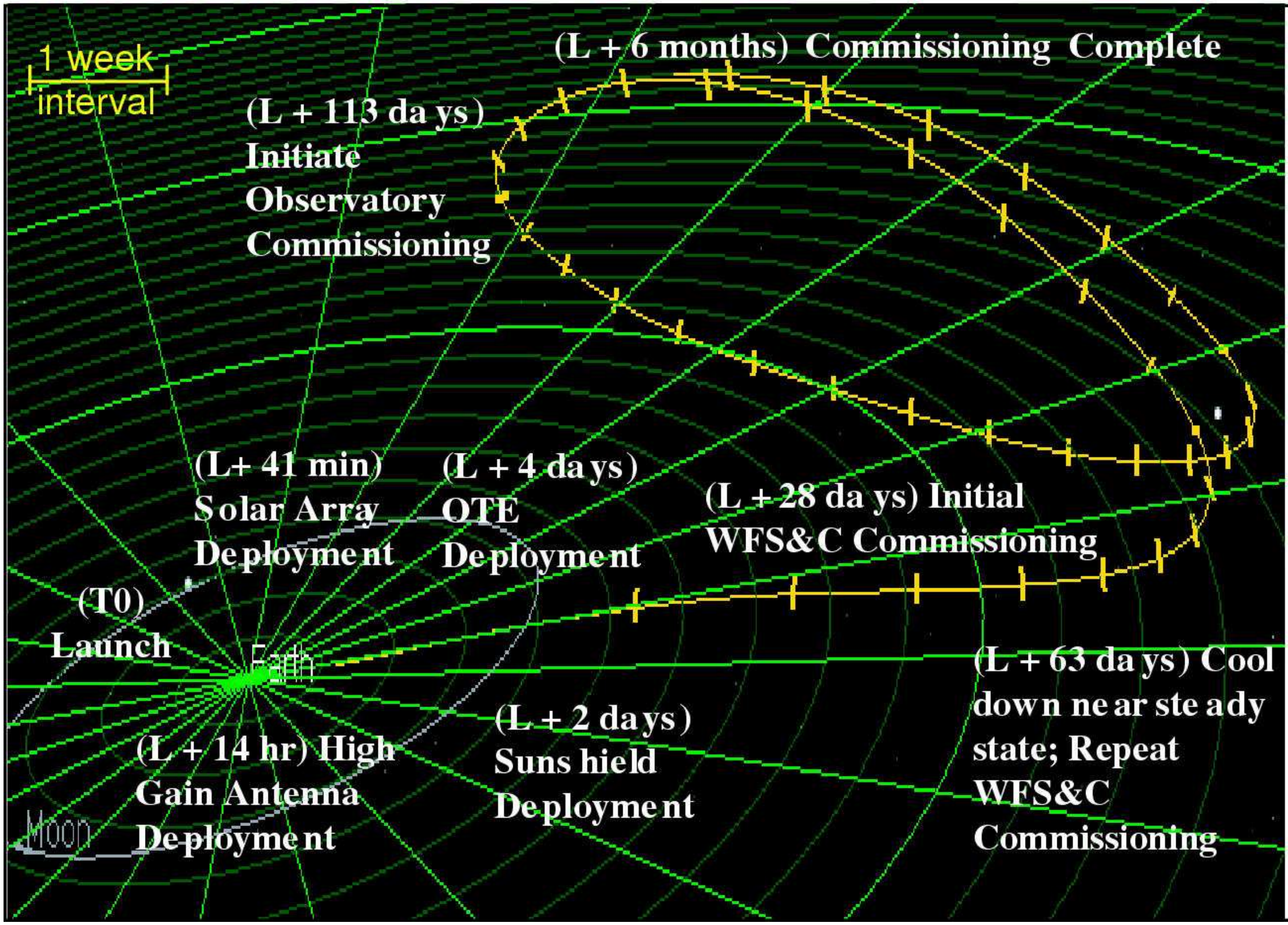
JWST LAUNCH

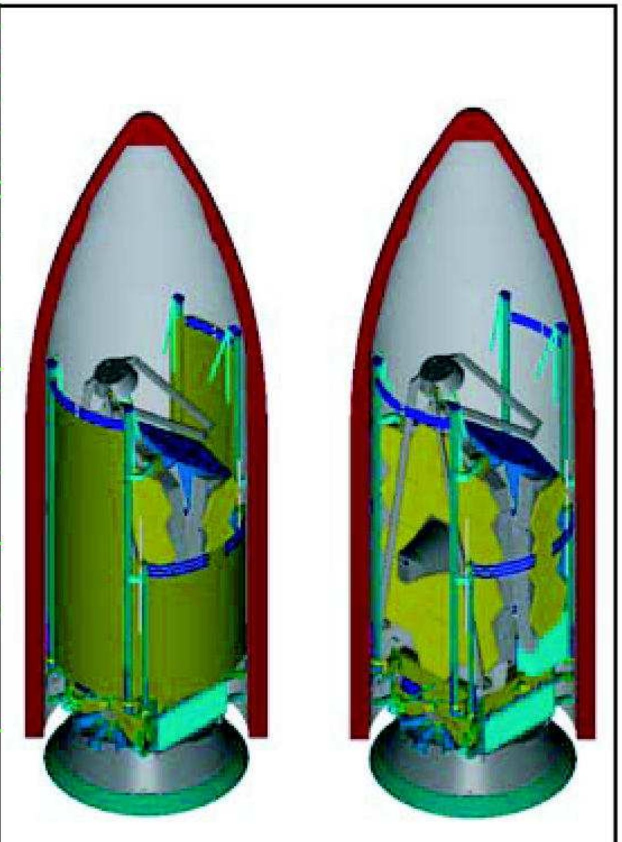
- LAUNCH VEHICLE IS AN ARIANE 5 ROCKET, SUPPLIED BY ESA
- SITE WILL BE THE ARIANESPACE'S ELA-3 LAUNCH COMPLEX NEAR KOUROU, FRENCH GUIANA

ARIANESPACE – ESA - NASA

- The JWST launch weight will be $\lesssim$6500 kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

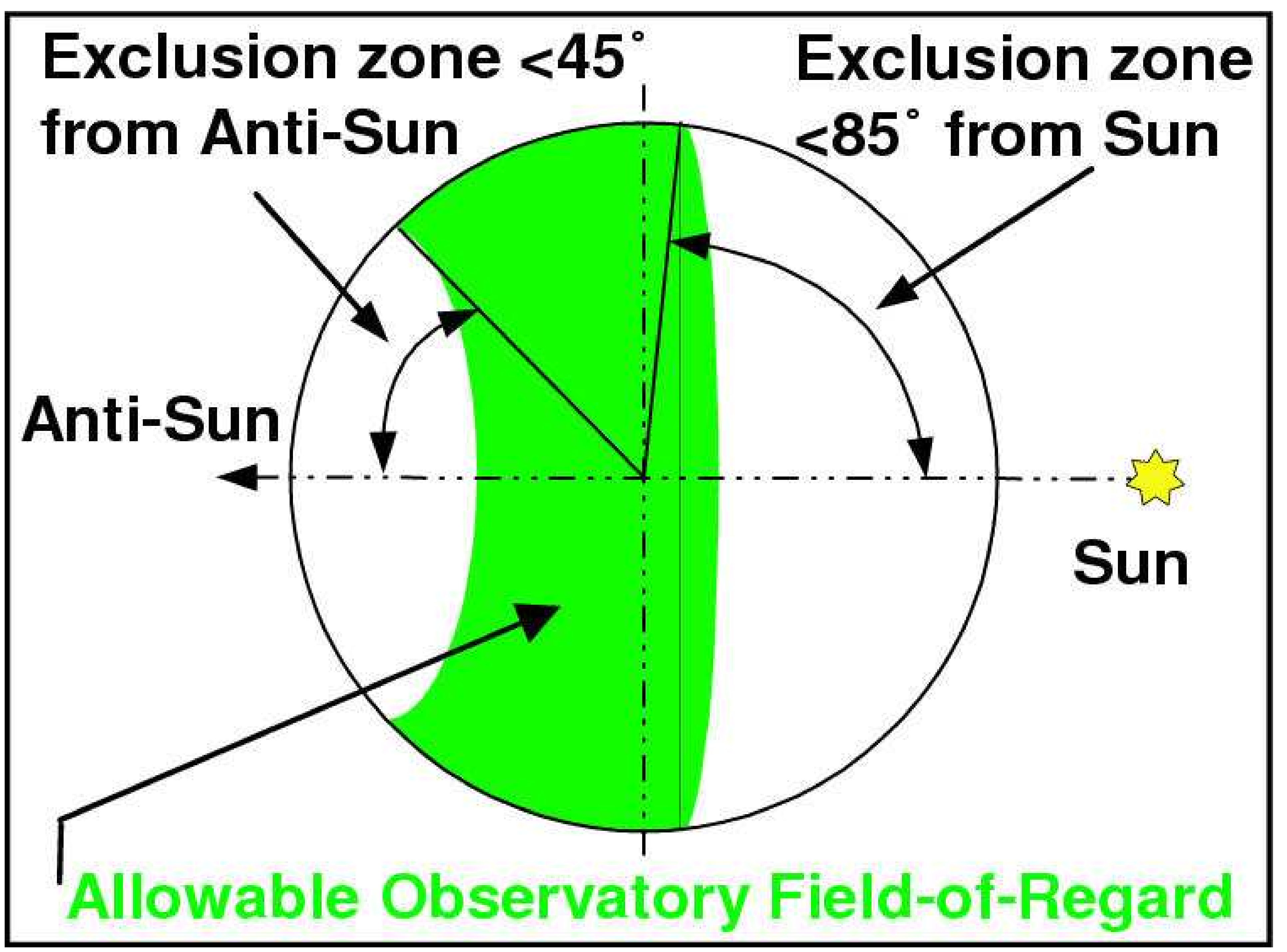
(3a) How will JWST travel to its L2 orbit?





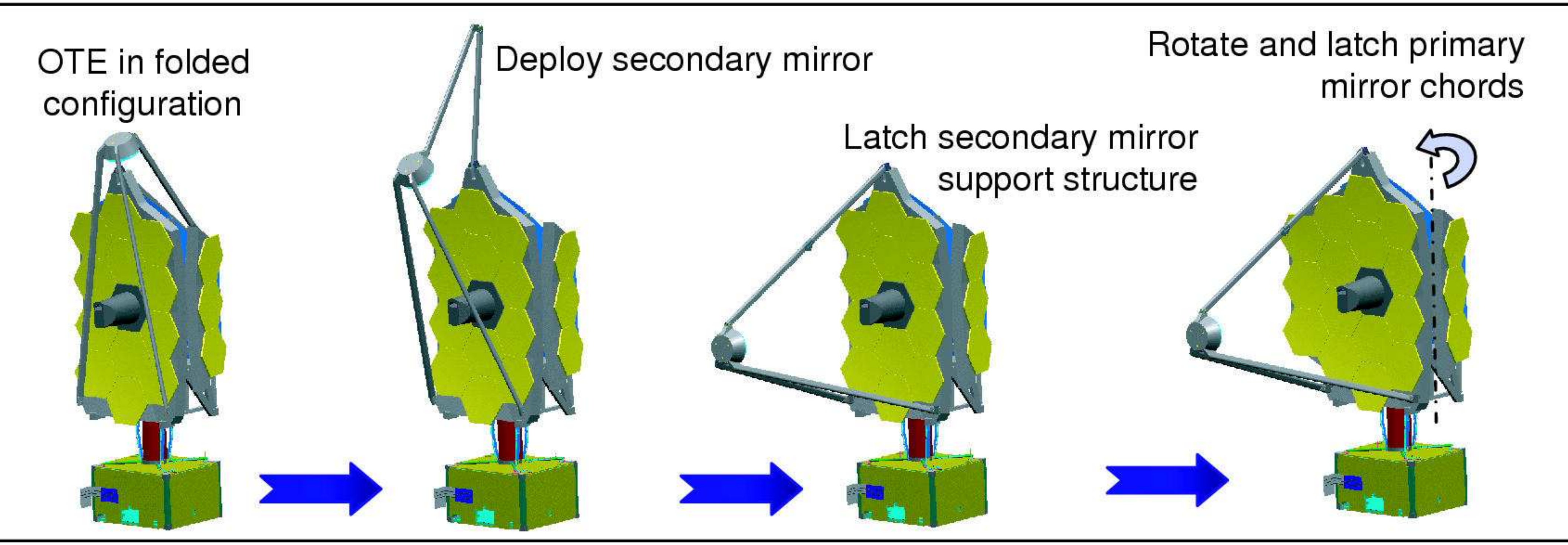
Stowed Observatory in 5meter shroud

- After launch in 2018 with an ESA Ariane-V, JWST will orbit around the Earth–Sun Lagrange point L2, 1.5 million km from Earth.
- JWST can cover the whole sky in segments that move along with the Earth, observe $\gtrsim$70% of the time, and send data back to Earth every day.



JWST can observe NEP+SEP continuously: Think of 1000-hr proposals!

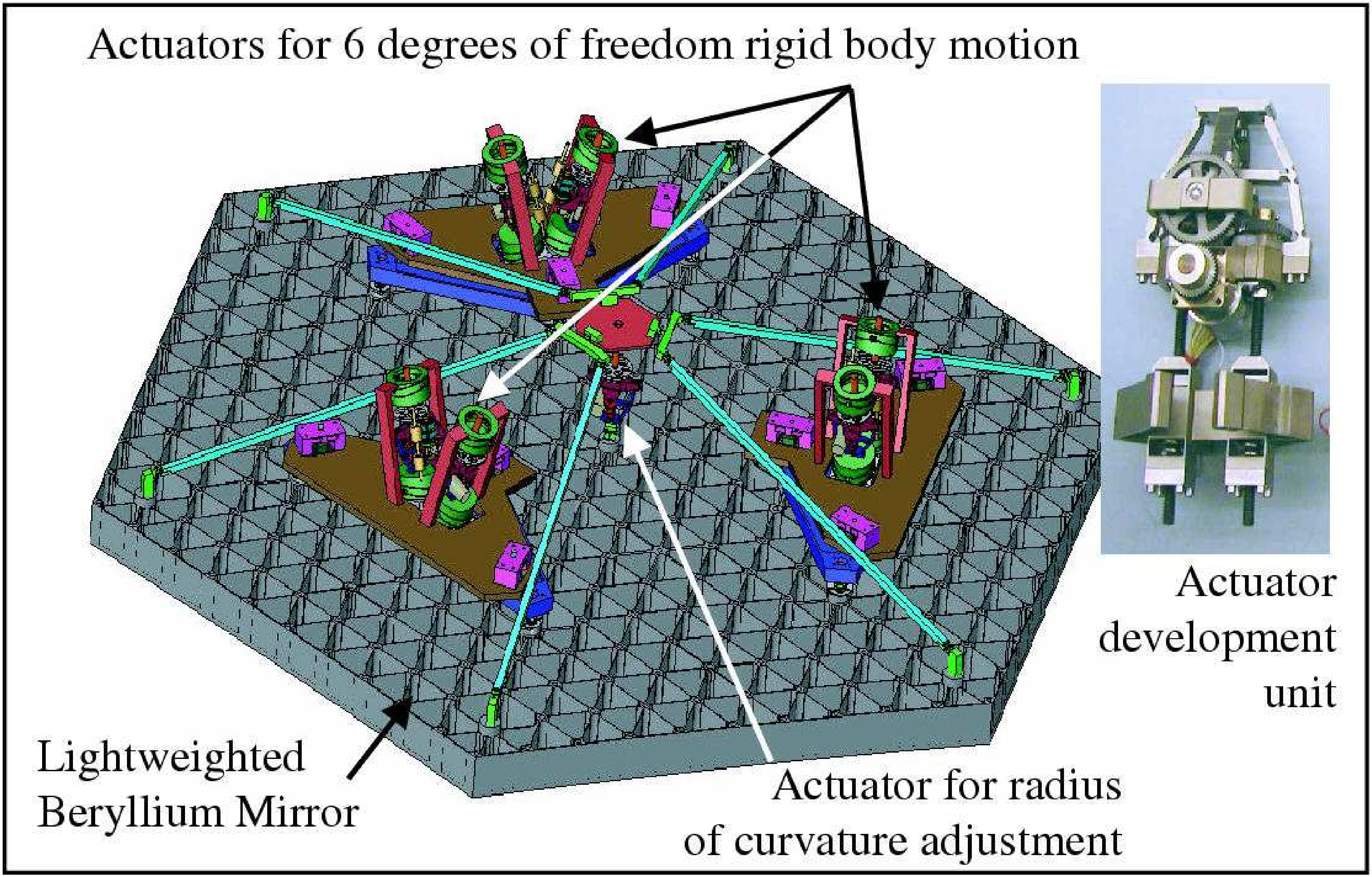
• (3b) How will JWST be automatically deployed?



- During its two month journey to L2, JWST will be automatically deployed, its instruments will be cooled, and be inserted into an L2 orbit.

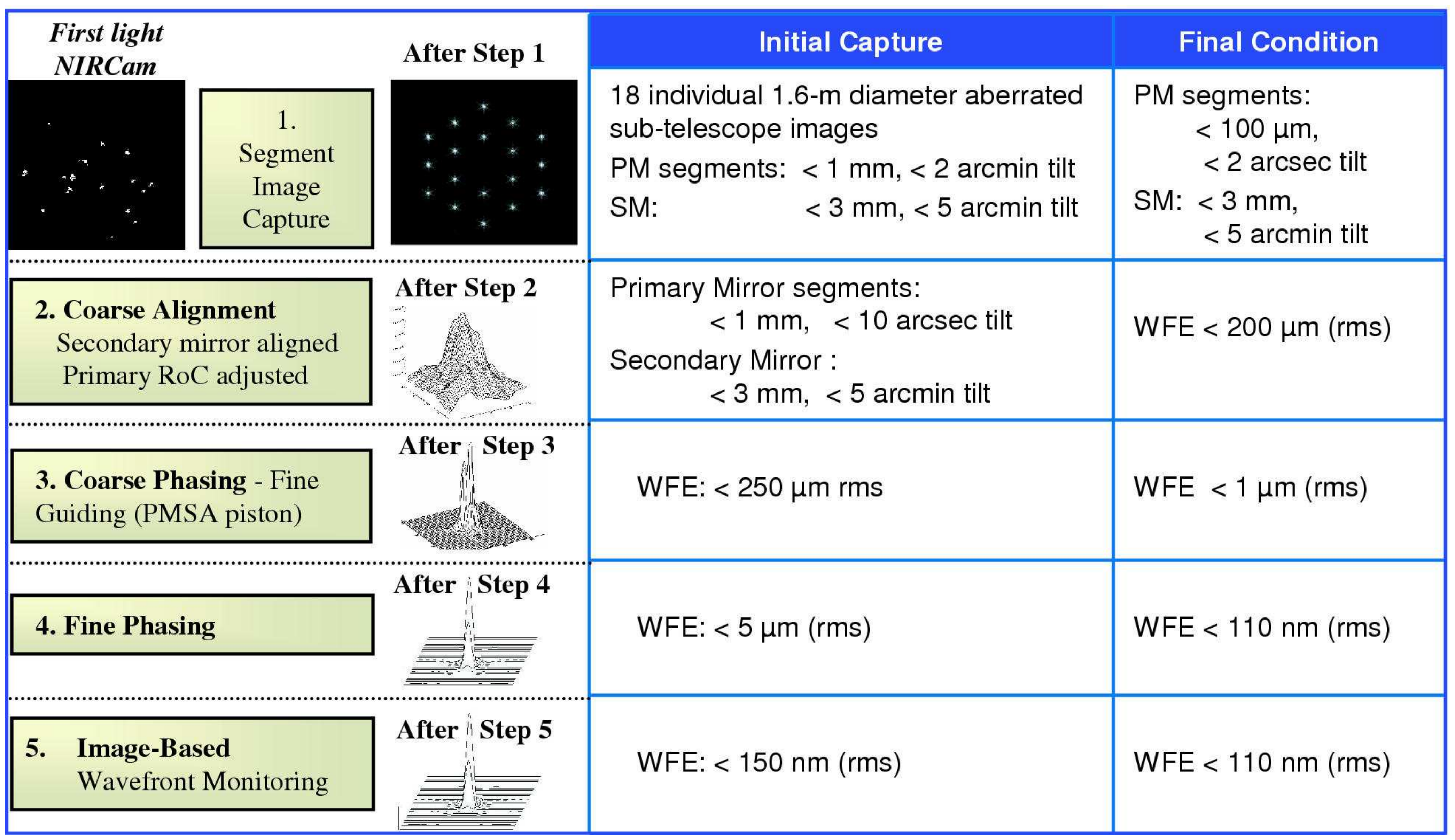
- The entire JWST deployment sequence will be tested several times on the ground — but only in 1-G: Component and system tests in Houston.

- Component fabrication, testing, & integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications.



Active mirror segment support through “hexapods”, similar to Keck.

Redundant & doubly-redundant mechanisms, quite forgiving against failures.

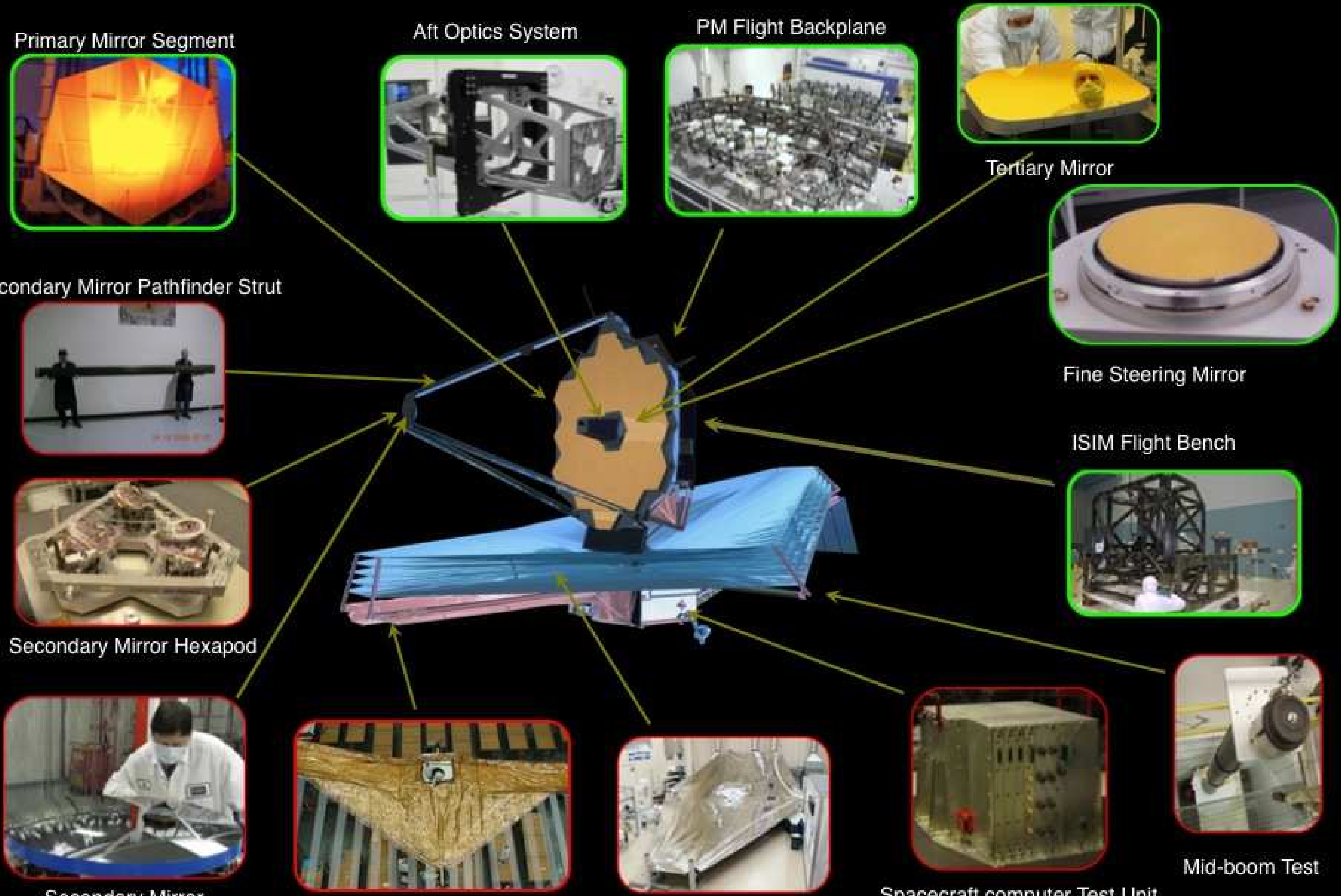


		Initial Capture	Final Condition
First light NIRCam 1. Segment Image Capture	After Step 1	18 individual 1.6-m diameter aberrated sub-telescope images PM segments: < 1 mm, < 2 arcmin tilt SM: < 3 mm, < 5 arcmin tilt	PM segments: < 100 μm, < 2 arcsec tilt SM: < 3 mm, < 5 arcmin tilt
2. Coarse Alignment Secondary mirror aligned Primary RoC adjusted	After Step 2	Primary Mirror segments: < 1 mm, < 10 arcsec tilt Secondary Mirror : < 3 mm, < 5 arcmin tilt	WFE < 200 μm (rms)
3. Coarse Phasing - Fine Guiding (PMSA piston)	After Step 3	WFE: < 250 μm rms	WFE < 1 μm (rms)
4. Fine Phasing	After Step 4	WFE: < 5 μm (rms)	WFE < 110 nm (rms)
5. **Image-Based** Wavefront Monitoring	After Step 5	WFE: < 150 nm (rms)	WFE < 110 nm (rms)

JWST's Wave Front Sensing and Control is similar to the Keck telescope.

In L2, need WFS updates every 10 days depending on scheduling/illumination.

JWST Hardware Status



Primary Mirror Segment

Aft Optics System

PM Flight Backplane

Tertiary Mirror

Secondary Mirror Pathfinder Strut

Fine Steering Mirror

ISIM Flight Bench

Secondary Mirror Hexapod

Secondary Mirror

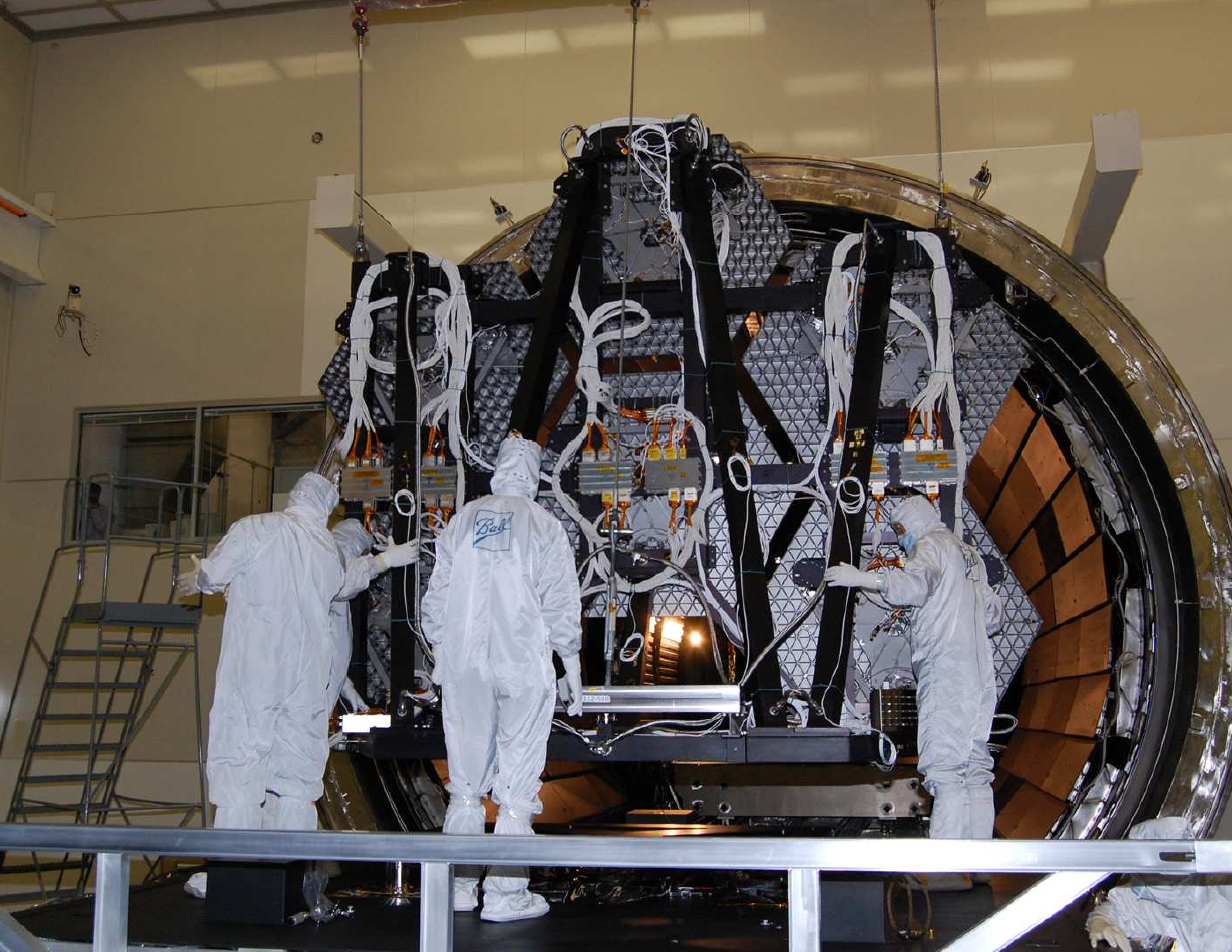
Membrane Mgmt

Pathfinder Membrane

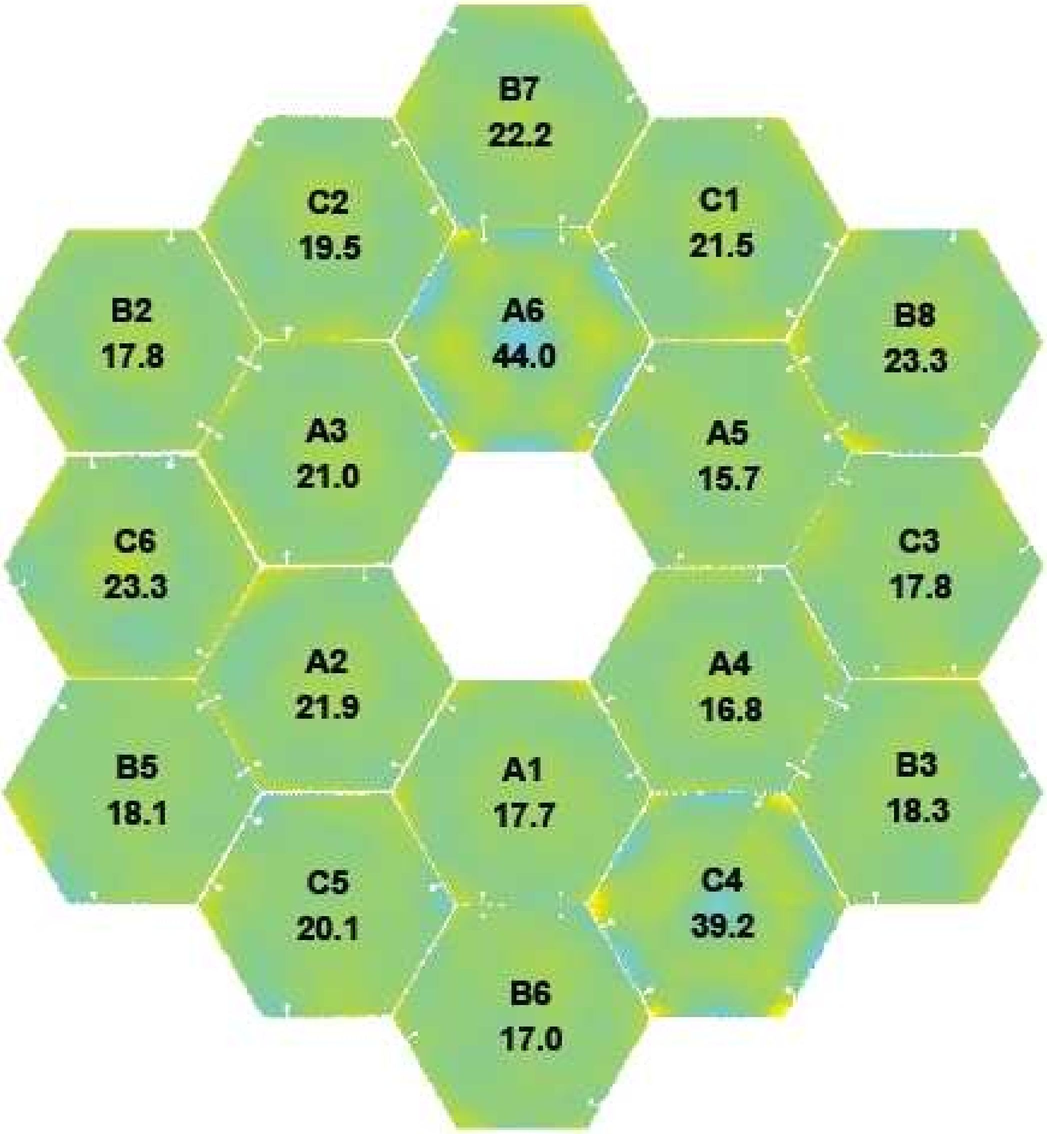
Spacecraft computer Test Unit

Mid-boom Test

Mirror Acceptance Testing

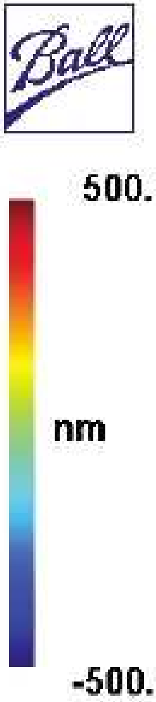

Ball

Primary Mirror Composite

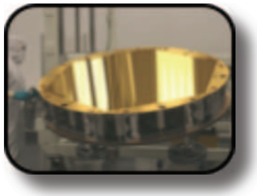


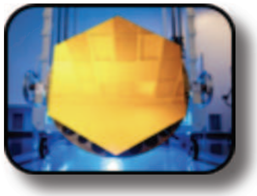
RMS: 23.2 nm

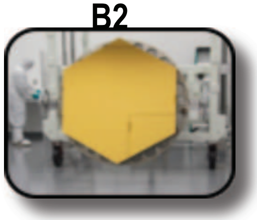
PV: 515.5 nm

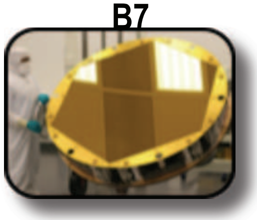


Family Portrait


A3


C1


B2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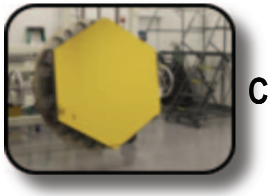
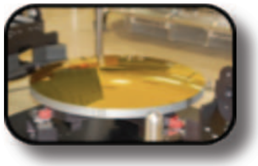
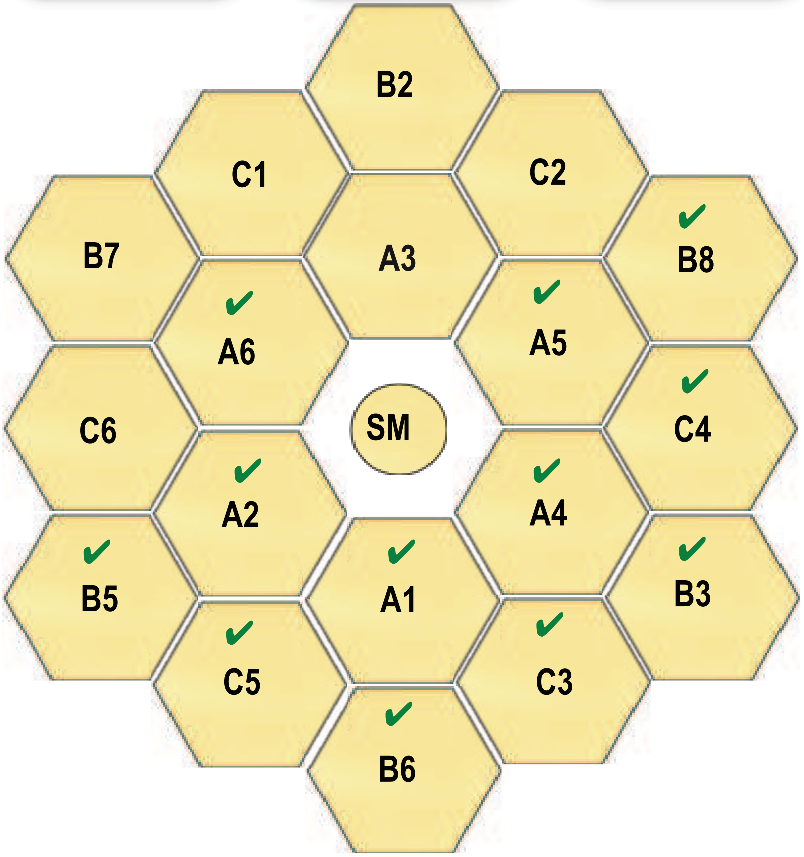

C2

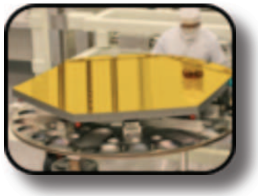

Secondary

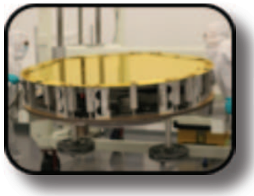

A6


B8


Tertiary ✓

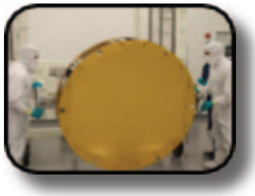



C6


A5

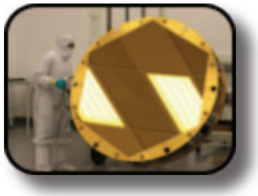

Fine Steering ✓

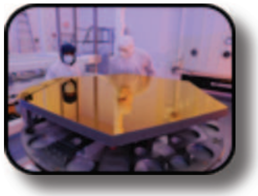

A2


C4


B5

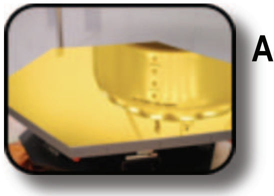

B3


C5


B6


A1

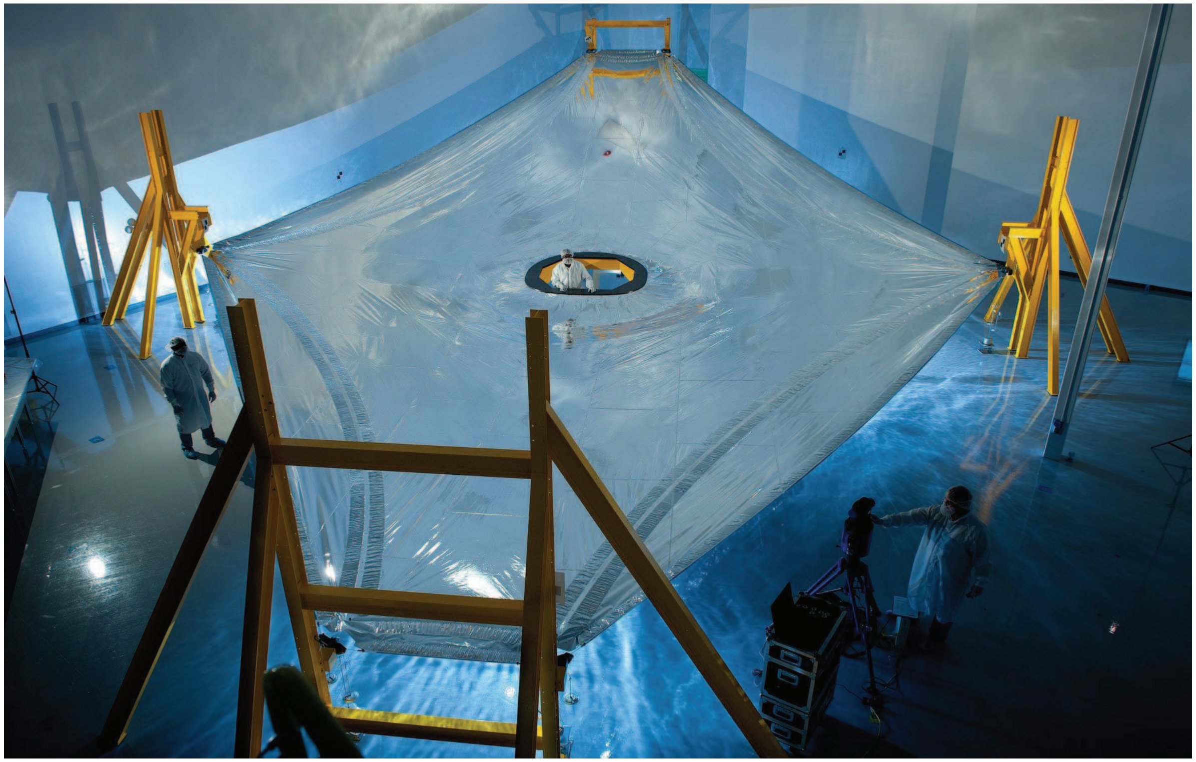

C3


A4

✓ Mirror segment has completed all thermal testing

Sunshield

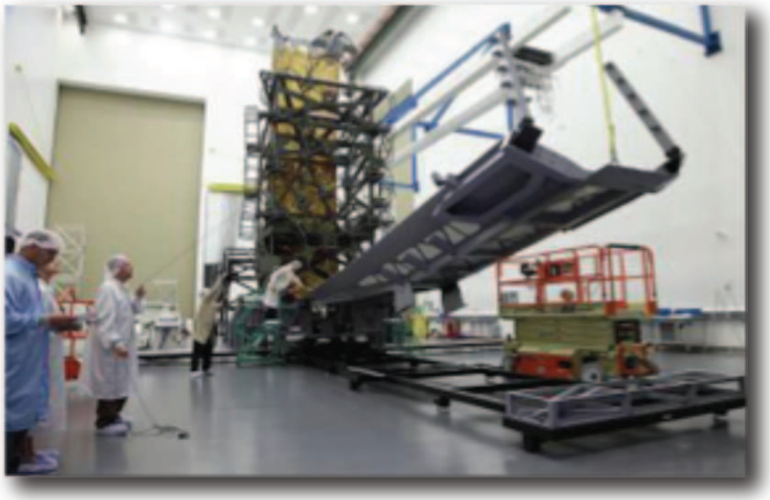
- **Template membrane build to flight-like requirements for verification of:**
  - Shape under tension to verify gradients and light line locations
  - Hole punching & hole alignment for membrane restraint devices (MRD)
  - Verification of folding/packing concept on full scale mockup
  - Layer 3 shape measurements completed



←Layer-3 template membrane under tension for 3-D shape measurements at Mantech

Full-scale JWST mockup with sunshield pallette

↓



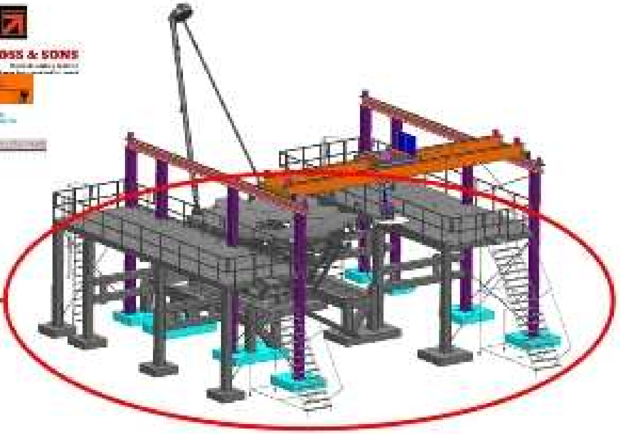
Telescope Assembly Ground Support Equipment

Ambient Optical Alignment Stand Complete

PMD

HM CROSS & SONS

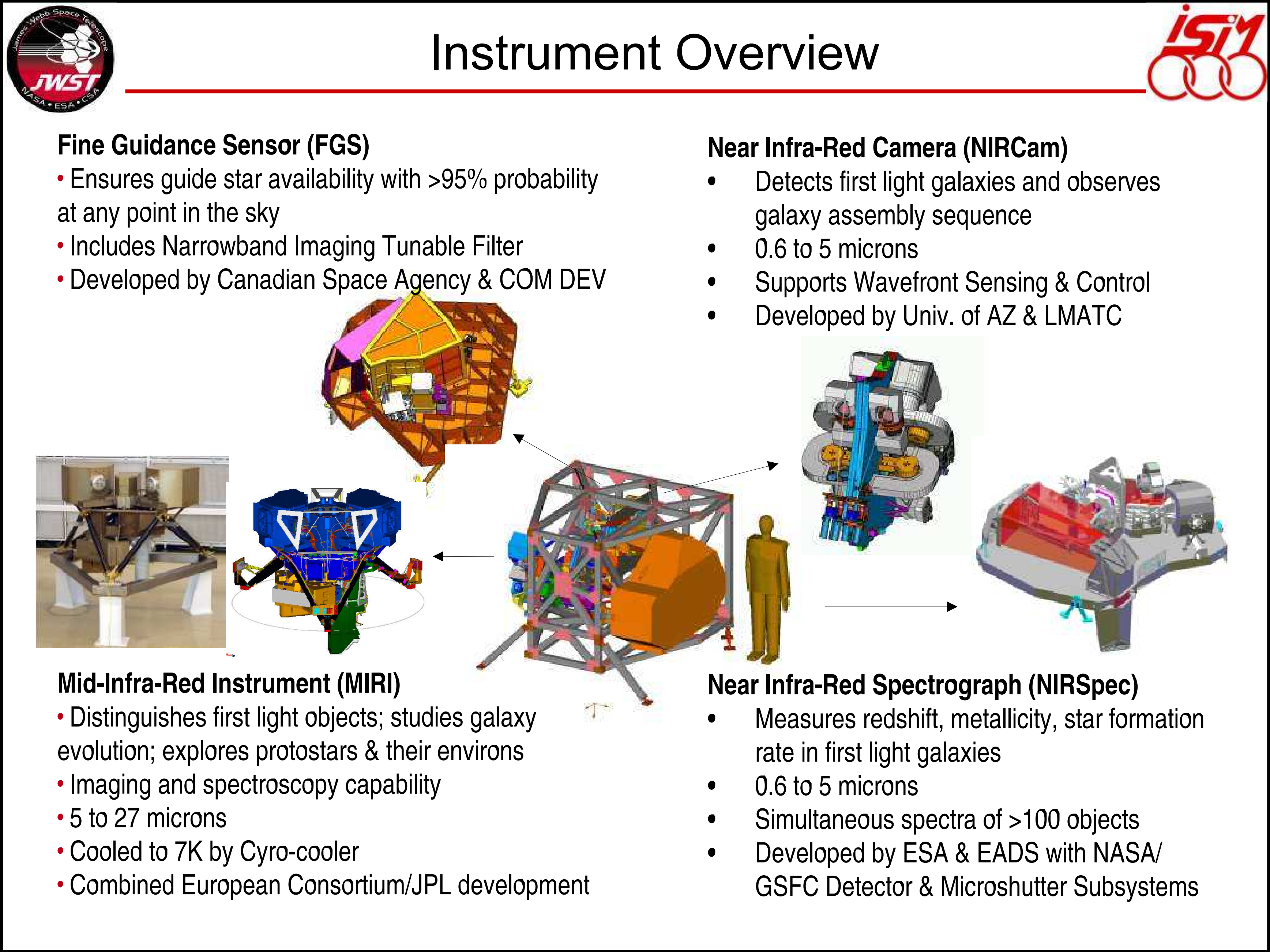
JPW



Hardware has been installed at GSFC approximately 8 weeks ahead of schedule

Landing a mirror onto backplane simulator

(3b) JWST instrument update: US (UofA, JPL), ESA, & CSA.



Instrument Overview

Fine Guidance Sensor (FGS)

- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

Near Infra-Red Camera (NIRCam)

- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC

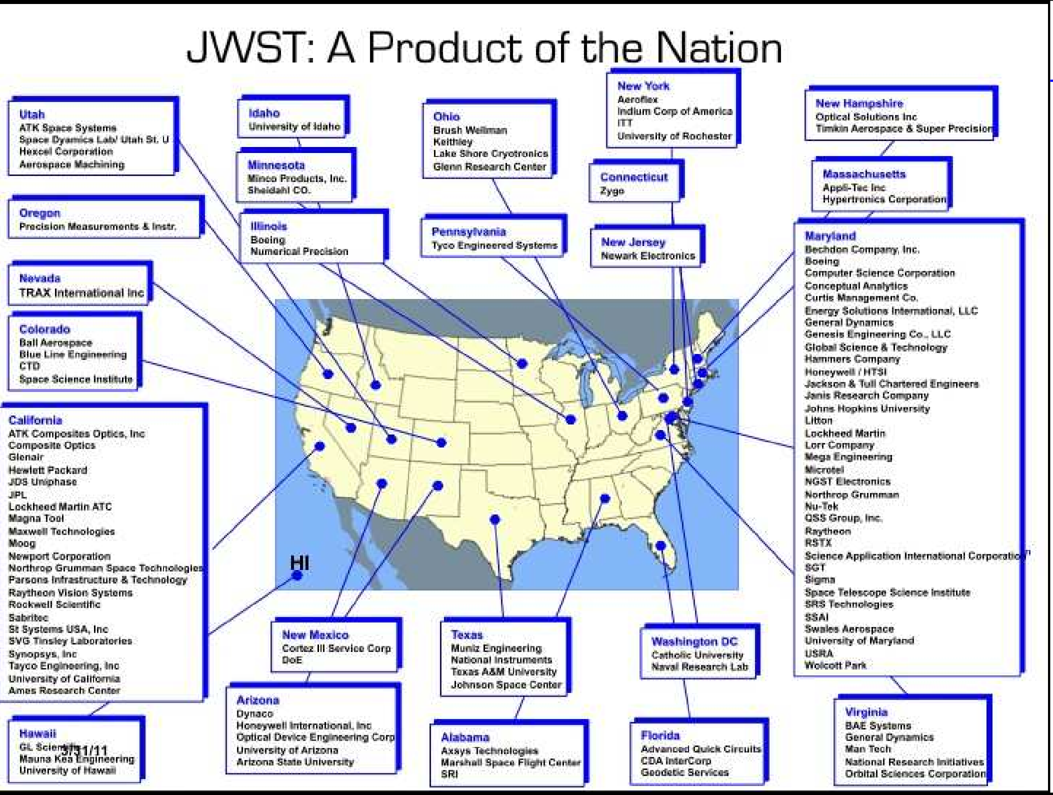
Mid-Infra-Red Instrument (MIRI)

- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

Near Infra-Red Spectrograph (NIRSpec)

- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/ GSFC Detector & Microshutter Subsystems

MIRI delivery 05/12; FGS 07/12; NIRCam 07/28/13(!), NIRSpec Fall 2013.



JWST: A Product of the Nation

Utah
ATK Space Systems
Space Dyamics Lab/ Utah St. U
Hexcel Corporation
Aerospace Machining

Idaho
University of Idaho

Minnesota
Minco Products, Inc.
Sheidahl CO.

Ohio
Brush Wellman
Keithley
Lake Shore Cryotronics
Glenn Research Center

New York
Aeroflex
Indium Corp of America
ITT
University of Rochester

New Hampshire
Optical Solutions Inc
Timkin Aerospace & Super Precision

Oregon
Precision Measurements & Instr.

Illinois
Boeing
Numerical Precision

Pennsylvania
Tyco Engineered Systems

Connecticut
Zygo

New Jersey
Newark Electronics

Massachusetts
Appli-Tec Inc
Hypertronics Corporation

Nevada
TRAX International Inc

Colorado
Ball Aerospace
Blue Line Engineering
CTD
Space Science Institute

Maryland
Bechdon Company, Inc.
Boeing
Computer Science Corporation
Conceptual Analytics
Curtis Management Co.
Energy Solutions International, LLC
General Dynamics
Genesis Engineering Co., LLC
Global Science & Technology
Hammers Company
Honeywell / HTSI
Jackson & Tull Chartered Engineers
Janis Research Company
Johns Hopkins University
Litton
Lockheed Martin
Lorr Company
Mega Engineering
Microtel
NGST Electronics
Northrop Grumman
Nu-Tek
QSS Group, Inc.
Raytheon
RSTX
Science Application International Corporation
SGT
Sigma
Space Telescope Science Institute
SRS Technologies
SSAI
Swales Aerospace
University of Maryland
USRA
Wolcott Park

California
ATK Composites Optics, Inc
Composite Optics
Glenair
Hewlett Packard
JDS Uniphase
JPL
Lockheed Martin ATC
Magna Tool
Maxwell Technologies
Moog
Newport Corporation
Northrop Grumman Space Technologies
Parsons Infrastructure & Technology
Raytheon Vision Systems
Rockwell Scientific
Sabritec
St Systems USA, Inc
SVG Tinsley Laboratories
Synopsys, Inc
Tayco Engineering, Inc
University of California
Ames Research Center

New Mexico
Cortez III Service Corp
DoE

Texas
Muniz Engineering
National Instruments
Texas A&M University
Johnson Space Center

Washington DC
Catholic University
Naval Research Lab

Arizona
Dynaco
Honeywell International, Inc
Optical Device Engineering Corp
University of Arizona
Arizona State University

Alabama
Axsys Technologies
Marshall Space Flight Center
SRI

Florida
Advanced Quick Circuits
CDA InterCorp
Geodetic Services

Virginia
BAE Systems
General Dynamics
Man Tech
National Research Initiatives
Orbital Sciences Corporation

Hawaii
GL Scientific
Mauna Kea Engineering
University of Hawaii

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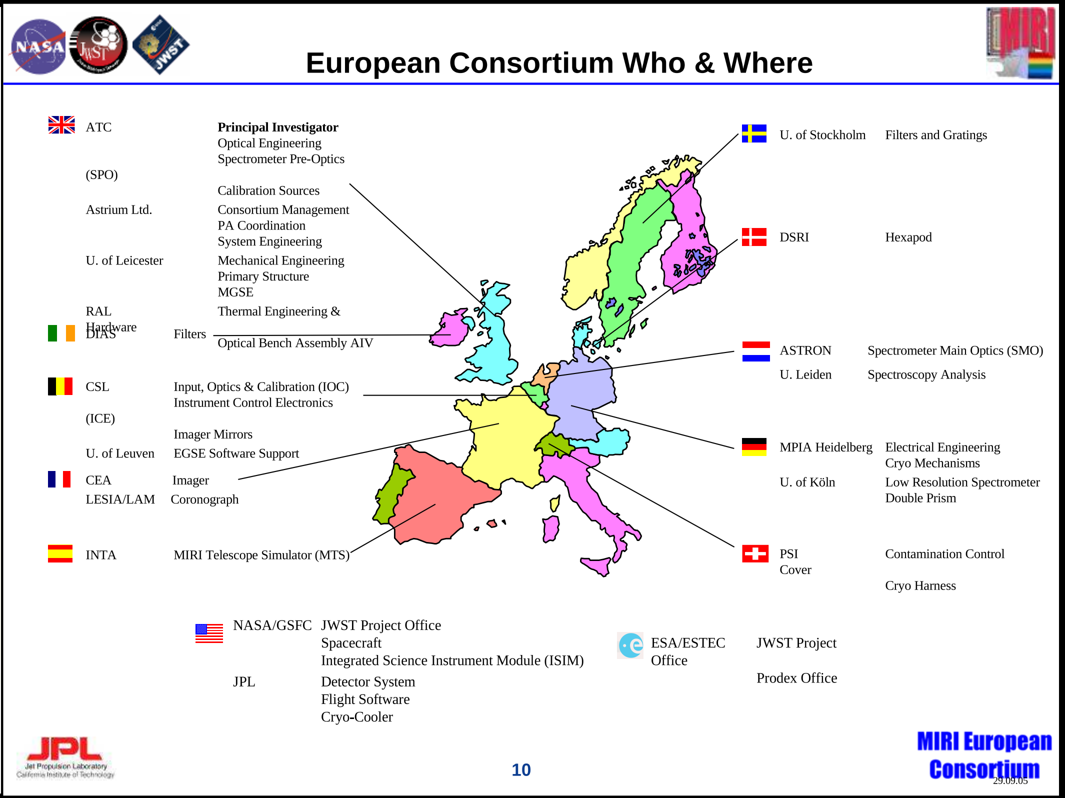


European Consortium Who & Where

ATC
Principal Investigator
Optical Engineering
Spectrometer Pre-Optics
(SPO)
Calibration Sources
Astrium Ltd.
Consortium Management
PA Coordination
System Engineering
U. of Leicester
Mechanical Engineering
Primary Structure
MGSE
RAL
Thermal Engineering &
Hardware
DIAS
Filters
Optical Bench Assembly AIV

CSL
Input, Optics & Calibration (IOC)
Instrument Control Electronics
(ICE)
Imager Mirrors
U. of Leuven
EGSE Software Support

CEA
Imager
LESIA/LAM
Coronograph

INTA
MIRI Telescope Simulator (MTS)

U. of Stockholm
Filters and Gratings

DSRI
Hexapod

ASTRON
Spectrometer Main Optics (SMO)
U. Leiden
Spectroscopy Analysis

MPIA Heidelberg
Electrical Engineering
Cryo Mechanisms
U. of Köln
Low Resolution Spectrometer
Double Prism

PSI
Contamination Control
Cover
Cryo Harness

NASA/GSFC
JWST Project Office
Spacecraft
Integrated Science Instrument Module (ISIM)
JPL
Detector System
Flight Software
Cryo-Cooler

ESA/ESTEC
Office
JWST Project
Prodex Office

Jet Propulsion Laboratory
California Institute of Technology

10

MIRI European Consortium

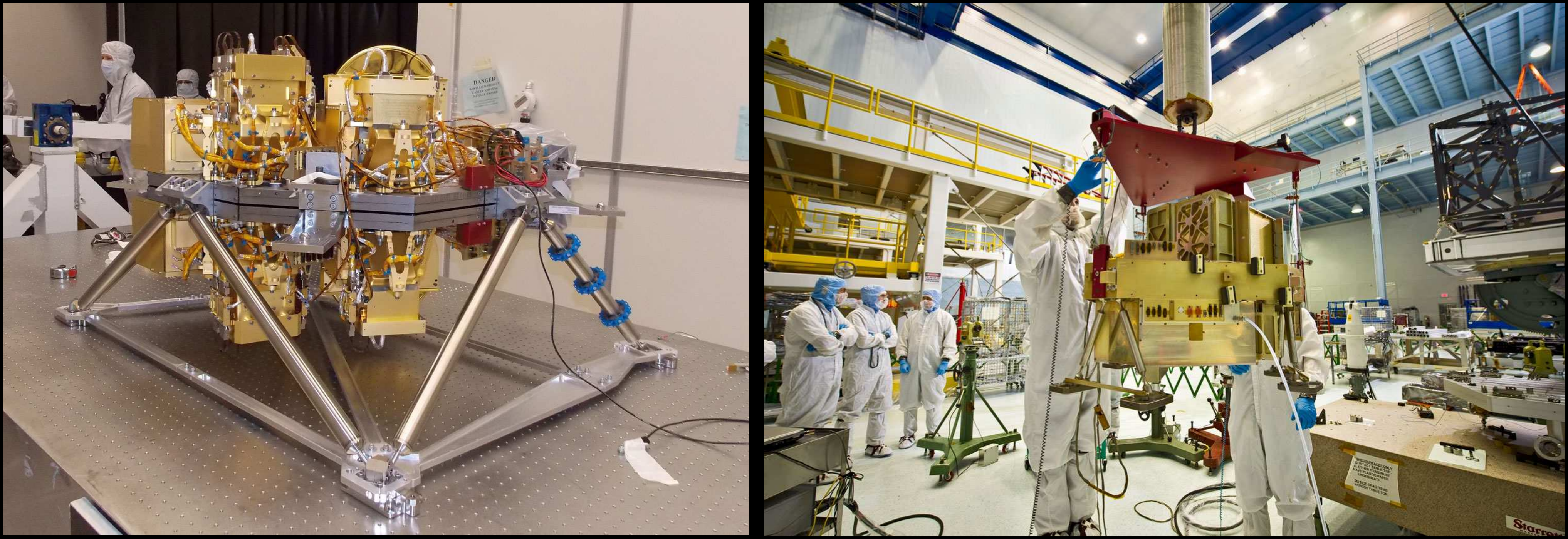
29.09.05

- JWST hardware made in 27 US States: $\gtrsim$75% of launch-mass finished.

- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.

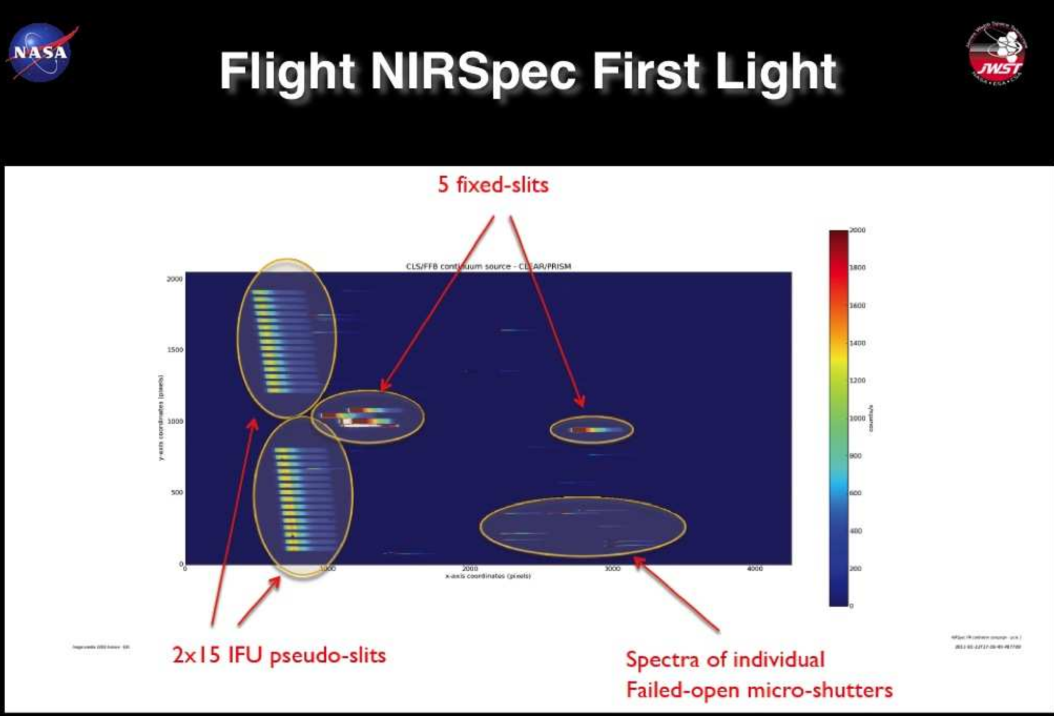
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.

- JWST NIRCam made by UofA and Lockheed.



JWST’s short-wavelength (0.6–5.0μm) imagers:

- NIRCam — built by UofA (AZ) and Lockheed (CA).
- Fine Guidance Sensor (& 1–5 μm grisms) — built by CSA (Montreal).
- FGS includes very powerful low-res Near-IR grism spectrograph (NIRISS).
- FGS delivered to GSFC 07/12; NIRCam delivered July 28, 2013!

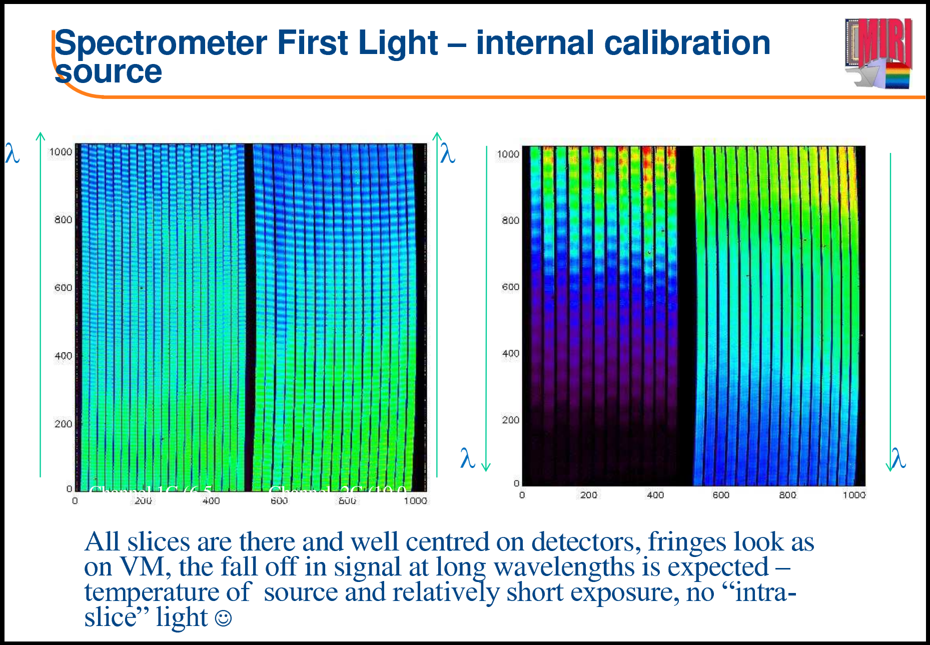

Flight NIRSpec First Light

JWST's short-wavelength (0.6–5.0μm) spectrograph:

- NIRSpec — built by ESA/ESTEC and Astrium (Munich).
- Flight build completed and tested with First Light in Spring 2011.

NIRSpec delivery to NASA/GSFC scheduled for Fall 2013.

Flight MIRI



Spectrometer First Light – internal calibration source

All slices are there and well centred on detectors, fringes look as on VM, the fall off in signal at long wavelengths is expected – temperature of source and relatively short exposure, no "intra-slice" light ☺

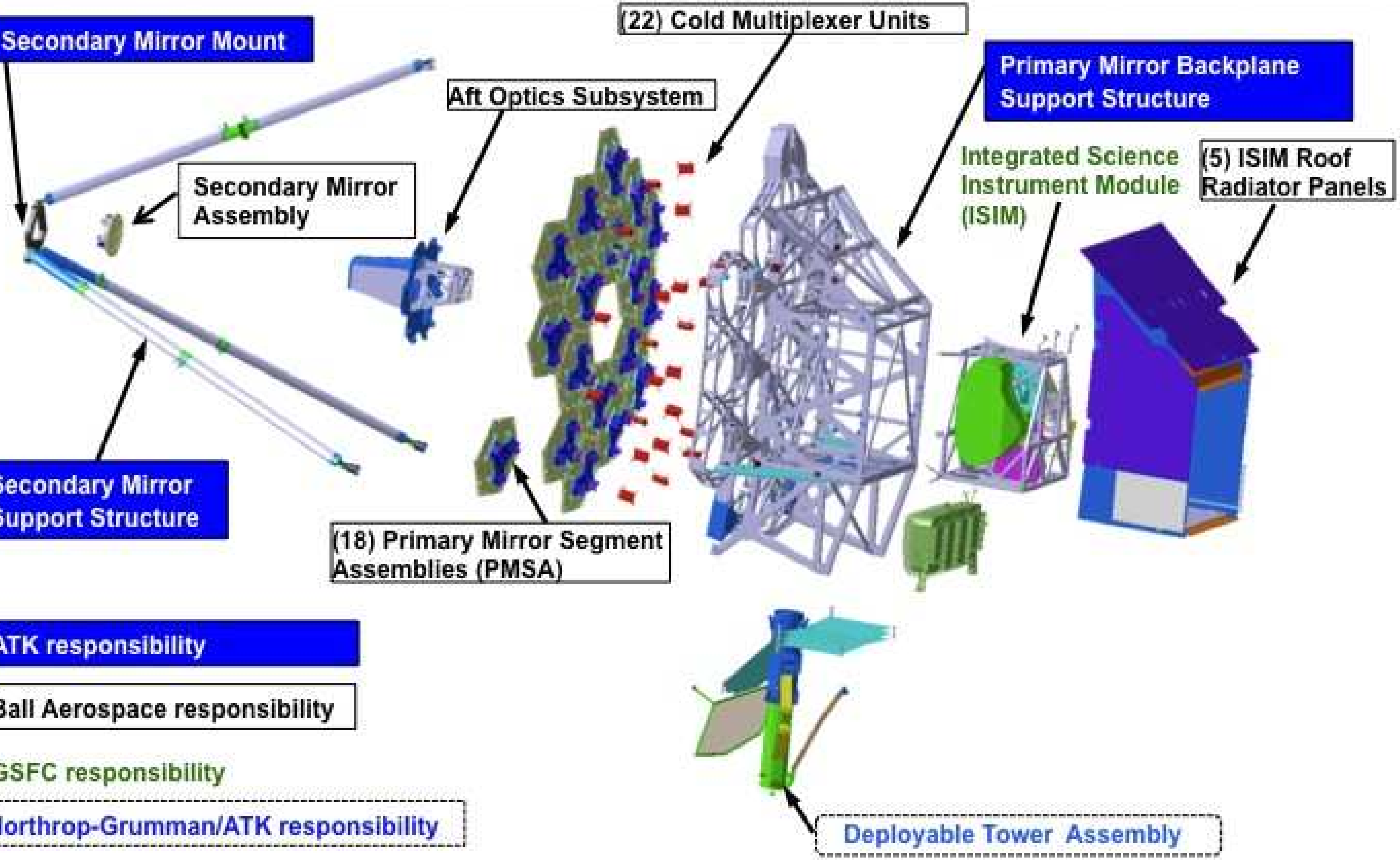
JWST's mid-infrared (5–29μm) camera and spectrograph:

- MIRI — built by ESA consortium of 10 ESA countries & NASA JPL.
- Flight build completed and tested with First Light in July 2011.

MIRI delivered to NASA/GSFC in May 2012.

OSIM: Here is where JWST Instruments inside ISIM are being tested.

TELESCOPE ARCHITECTURE



Secondary Mirror Mount

(22) Cold Multiplexer Units

Primary Mirror Backplane Support Structure

Aft Optics Subsystem

Secondary Mirror Assembly

Integrated Science Instrument Module (ISIM)

(5) ISIM Roof Radiator Panels

Secondary Mirror Support Structure

(18) Primary Mirror Segment Assemblies (PMSA)

Deployable Tower Assembly

ATK responsibility

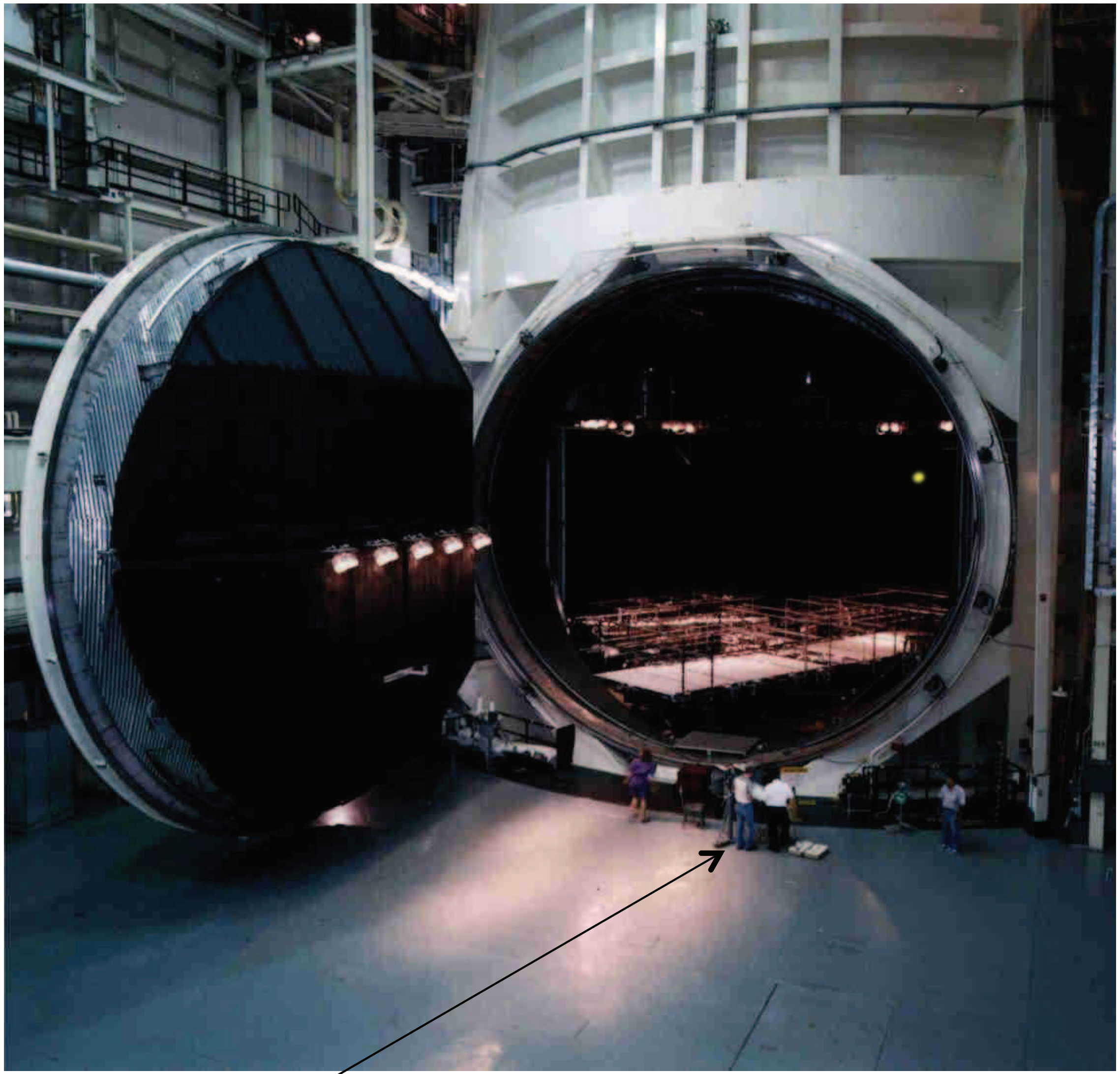
Ball Aerospace responsibility

GSFC responsibility

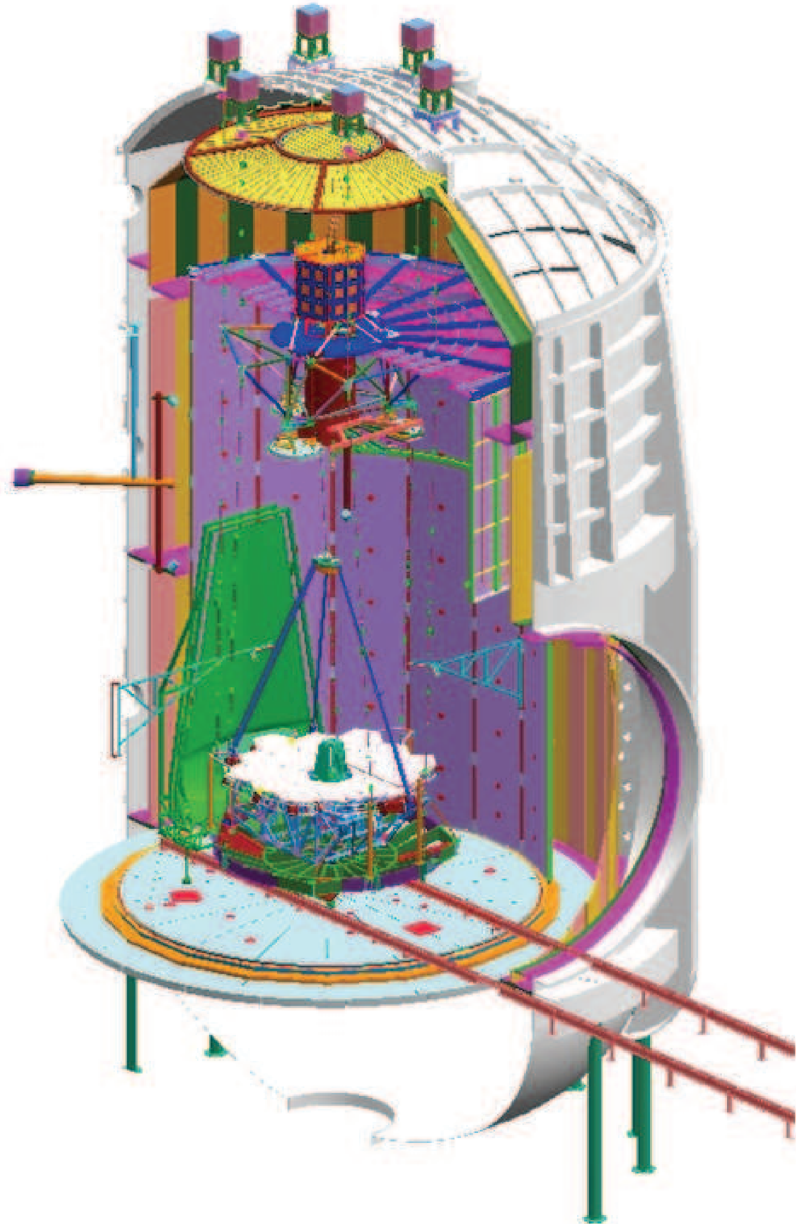
Northrop-Grumman/ATK responsibility

3/31/11

OTE Testing – Chamber A at JSC



Notice people for scale



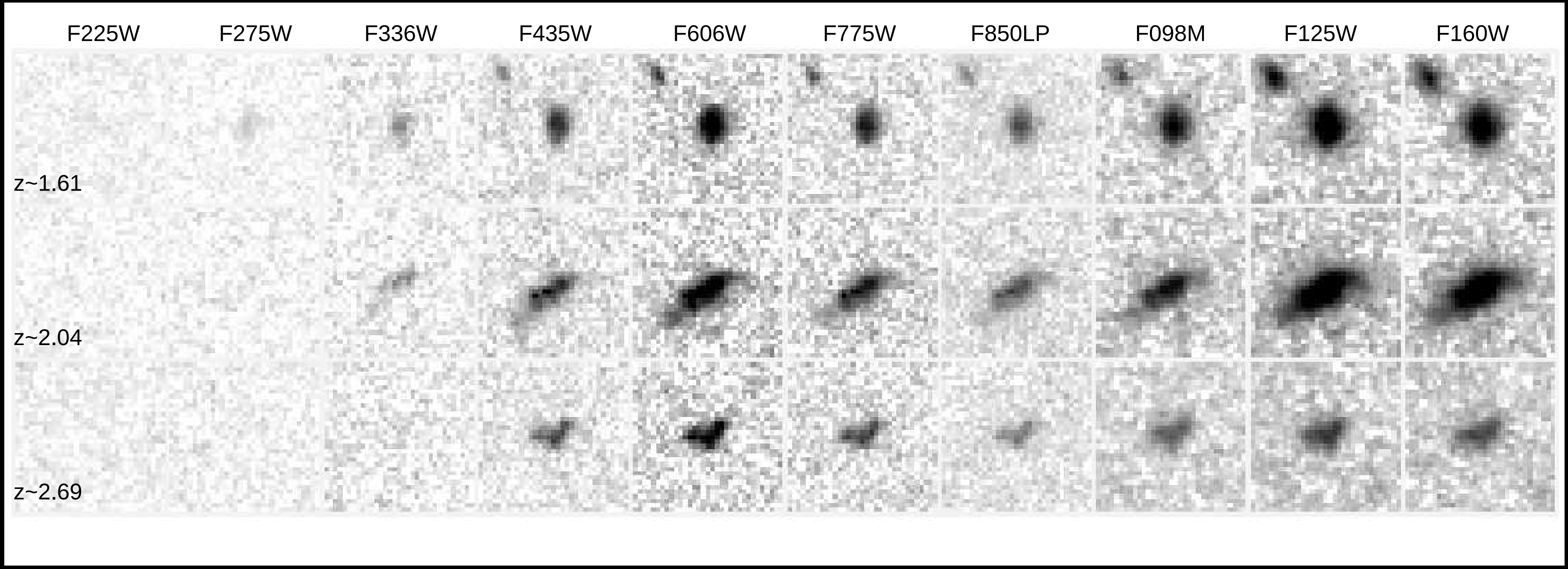
Will be the largest cryo vacuum test chamber in the world

OTIS: Largest TV chamber in world: will test whole JWST in 2015–2016.

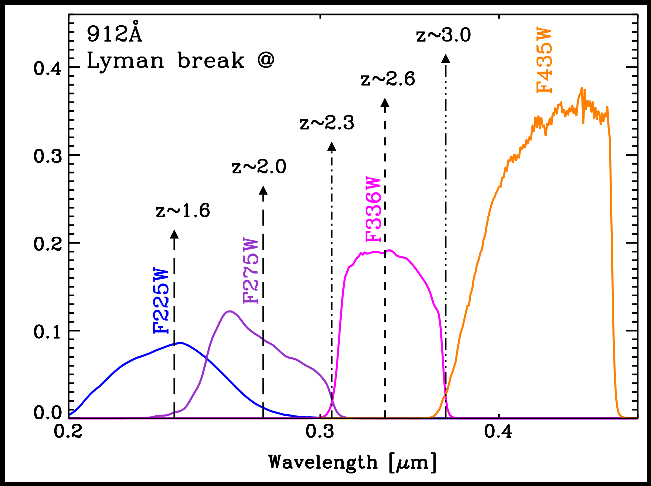
(4) How can JWST measure Galaxy Assembly and SMBH/AGN Growth?

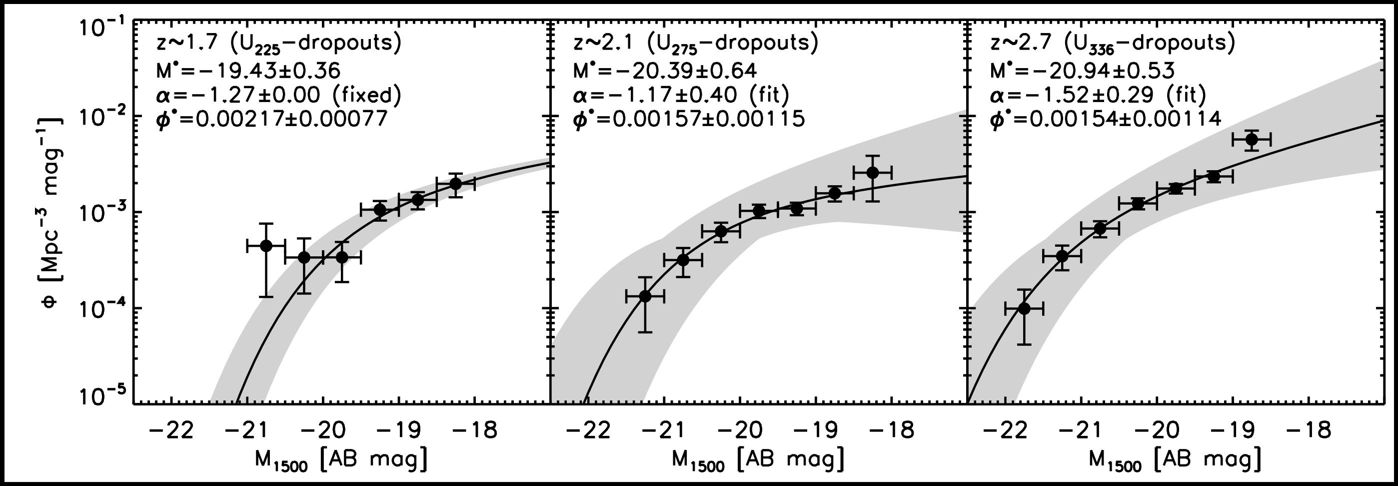
10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-$\boldsymbol{\sigma}$) over 40 arcmin^{2} at 0.07–0.15" FWHM from 0.2–1.7μm (UVUBVizYJH).

JWST adds 0.05–0.2" FWHM imaging to AB$\simeq$31.5 mag (1 nJy) at 1–5μm, and 0.2–1.2" FWHM at 5–29μm, tracing young+old SEDs & dust.



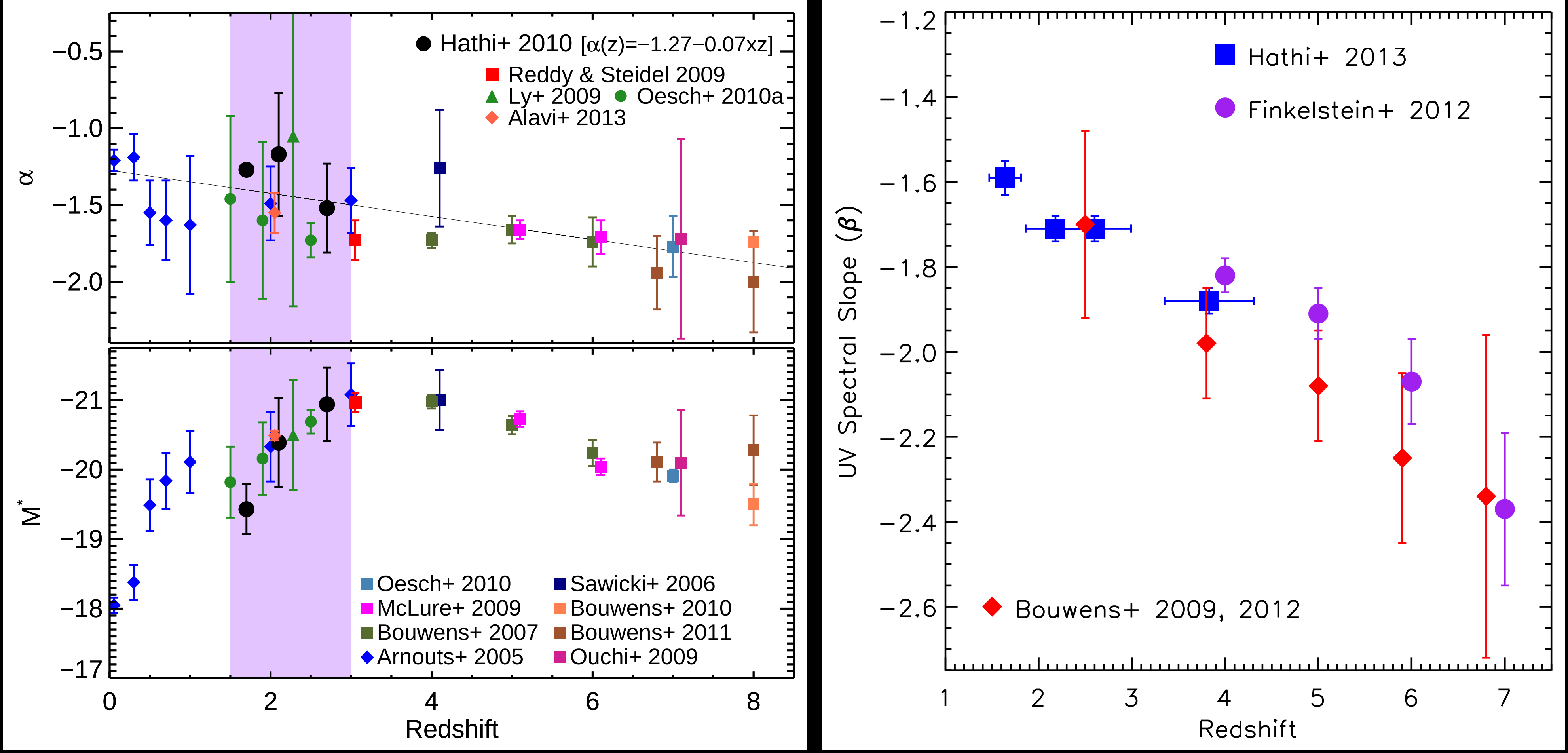
Lyman break galaxies at the peak of cosmic SF ($z\simeq1$-3; Hathi$^+$ 2010, 2013)





- JWST will similarly measure faint-end LF-slope evolution for $1\lesssim z\lesssim12$.

(e.g., Bouwens$^+$ 2010, 2013; Hathi$^+$ 2010, 2013; Oesch $^+$ 2010; 2013; Ellis$^+$2012; Robinson$^+$ 2013).



Evol of LF-slope α (top), M^* (bottom), & UV-slope β (right; Hathi$^+$ 10,13)

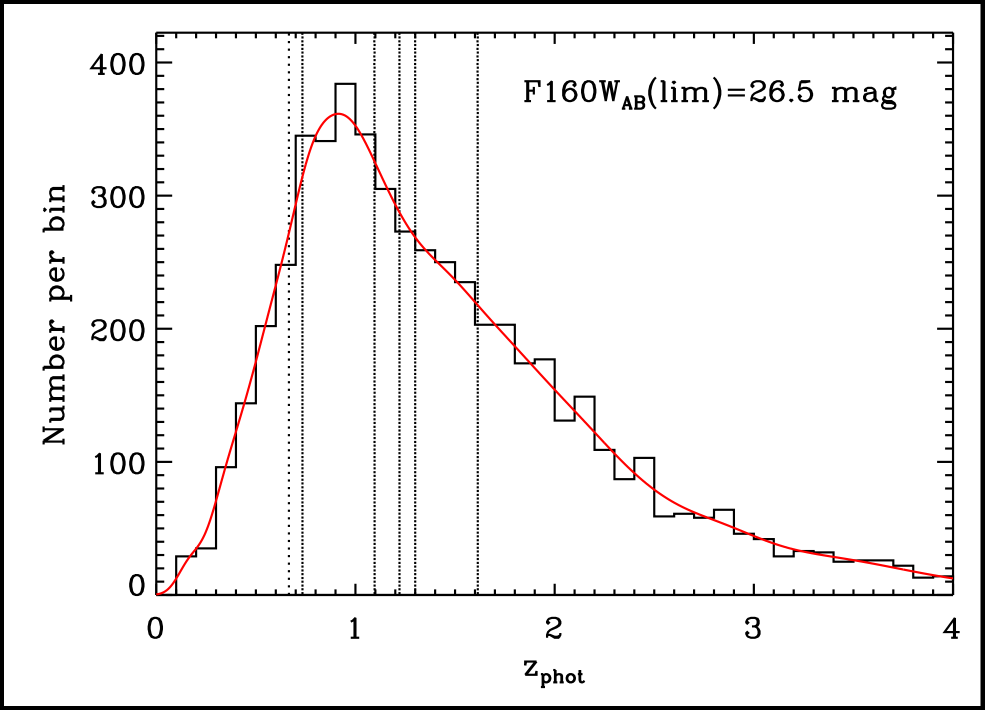
- JWST z$\gtrsim$8, expect faint-end slope $\alpha\simeq$–2.0 (Bouwens 2012).
- JWST z$\gtrsim$8, expect UV $\beta\lesssim$–2.2 (Finkelstein$^+$12; Jiang 2013).

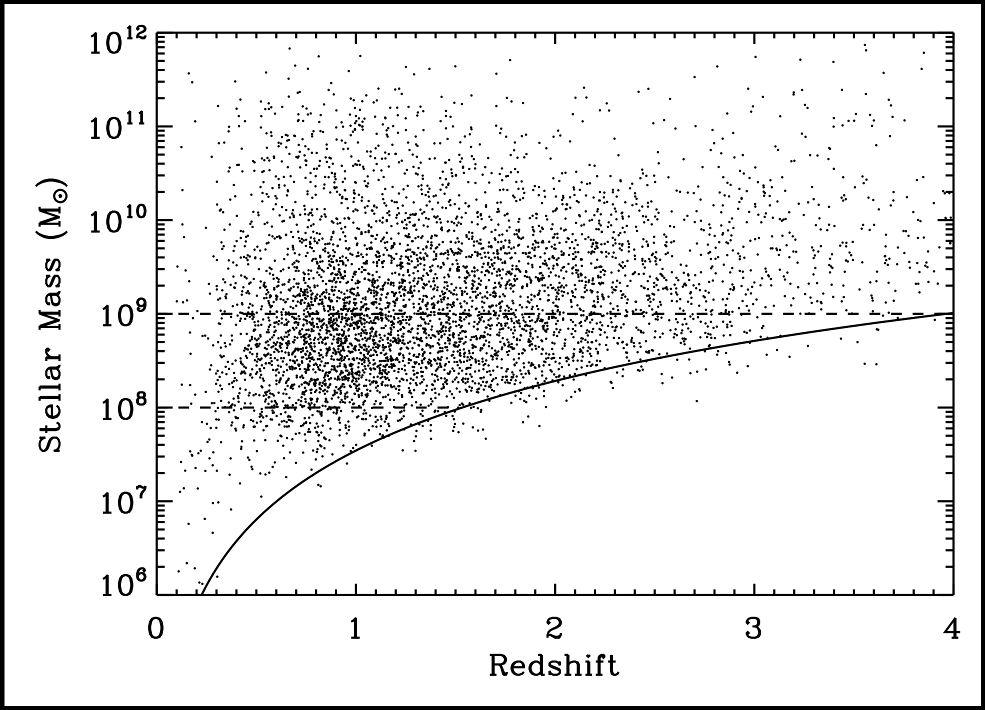
$\Rightarrow$ Both important for cosmic reionization at z$\gtrsim$6 by dwarf galaxies.

NOTE: Faint-end slope α–1.5 to –1.6 at z$\simeq$1.5–2 (also Siana 2012).

- JWST at z$\gtrsim$8: see if characteristic luminosity M^* $\gtrsim$–19 mag.

$\Rightarrow$ Could cause significant gravitational lensing bias at z$\gtrsim$8–10.





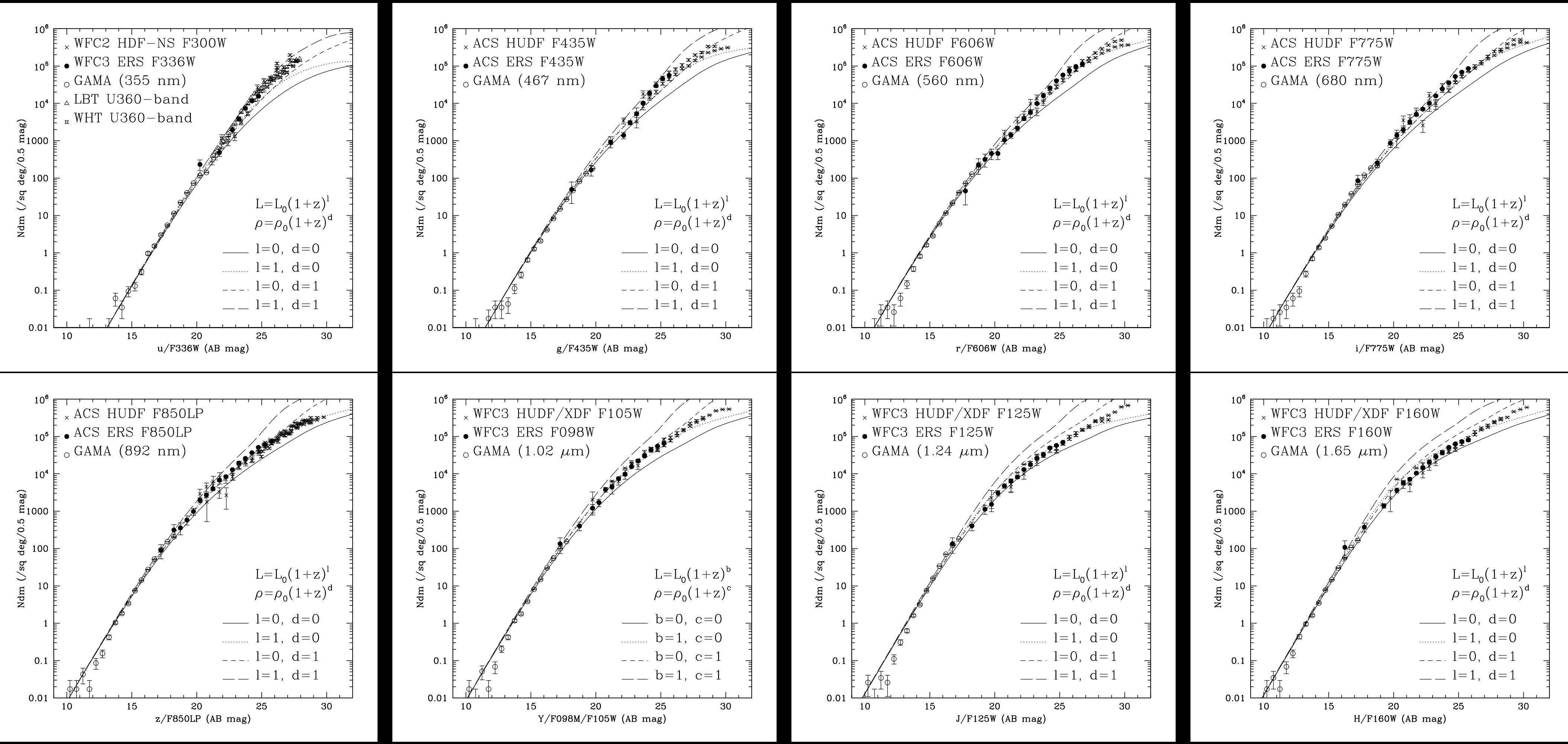
WFC3 ERS 10-band redshift estimates accurate to $\lesssim$4% with small systematic errors (Hathi et al. 2010, 2013), resulting in a reliable N(z).

- Measure masses of faint galaxies to AB=26.5 mag, tracing the process of galaxy assembly: downsizing, merging, (& weak AGN growth?).

⇒ Median redshift in (medium-)deep fields is z_{med} $\simeq$1.5–2.

- JWST will trace mass assembly and dust content $\lesssim$5 mag deeper from $z\simeq$1–12, with nanoJy sensitivity from 0.7–5μm.

Panchromatic Galaxy Counts from $\lambda \simeq$0.2–2μm for AB$\simeq$10–31 mag



Data: GALEX, GAMA, HST ERS + HUDF/XDF ACS+WFC3 (*e.g.*, Windhorst et al. 2011; Ellis$^+$ 2012; Illingworth$^+$ 2012; Teplitz$^+$2013): F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F098M/F105W, F125W, F140W, F160W.

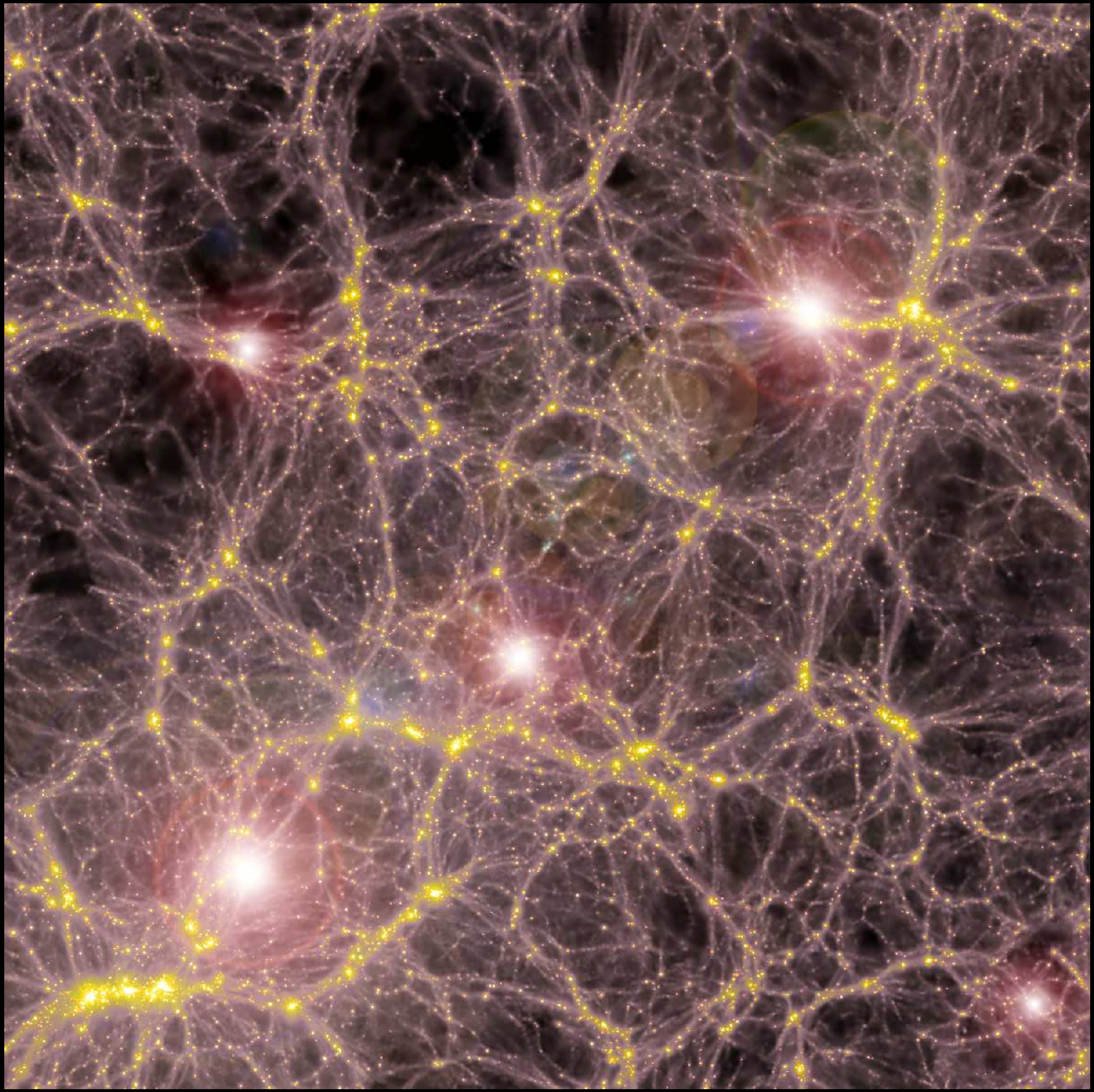
- HUDF: Faint-end near-IR mag-slopes $\simeq$ 0.22±0.02 to AB$\lesssim$31 mag $\Longleftrightarrow$

At z_{med} $\simeq$1.6, faint-end LF-slope $\alpha\simeq$–1.5–1.6 to M$_{AB}\simeq$–14 mag !

$\Rightarrow$ Extrapolation of LF(z$\gtrsim$2) to AB$\simeq$–10 is entirely plausible.

- JWST can see objects at AB$\gtrsim$32 mag. Confusion limit at AB$\lesssim$34 mag.

(4a) How will JWST Observe First Light and Reionization?

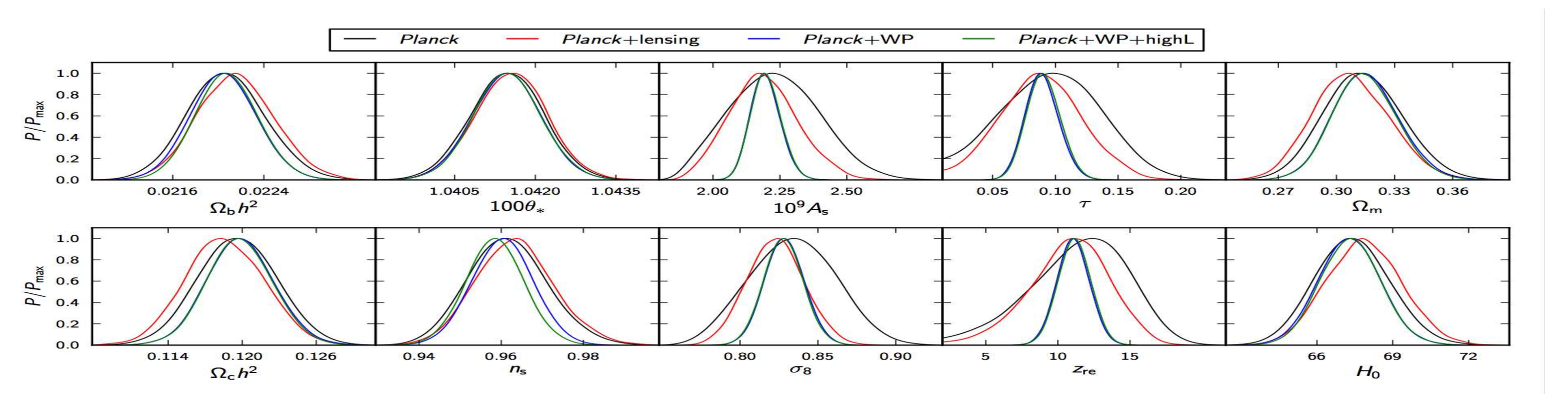


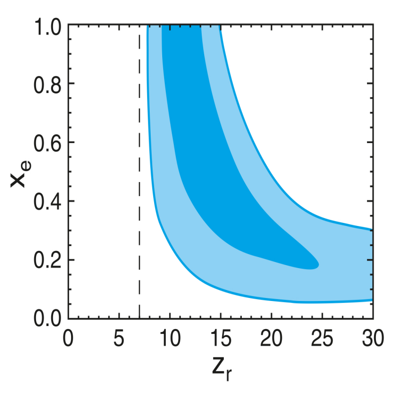
- Detailed Hydrodynamical models (e.g., V. Bromm) suggest that massive Pop III stars may have reionized universe at redshifts $z \lesssim 10$–30 (First Light).

- A this should be visible to JWST as the first Pop III stars and surrounding (Pop II.5) star clusters, and perhaps their extremely luminous supernovae at $z \simeq 10 \longrightarrow 30$.

We must make sure we theoretically understand the likely Pop III mass-range, their IMF, their duplicity and clustering properties, their SN-rates, etc.

Implications of the WMAP year-9 & Planck results for JWST science:





HST/WFC3 $z\lesssim$7–9 ⟵ ⟶ JWST $z\simeq$8–25

The year-9 WMAP data provided better foreground removal (Komatsu$^+$ 2011; Hinshaw$^+$ 2012; but see: Planck XVI 2013.)

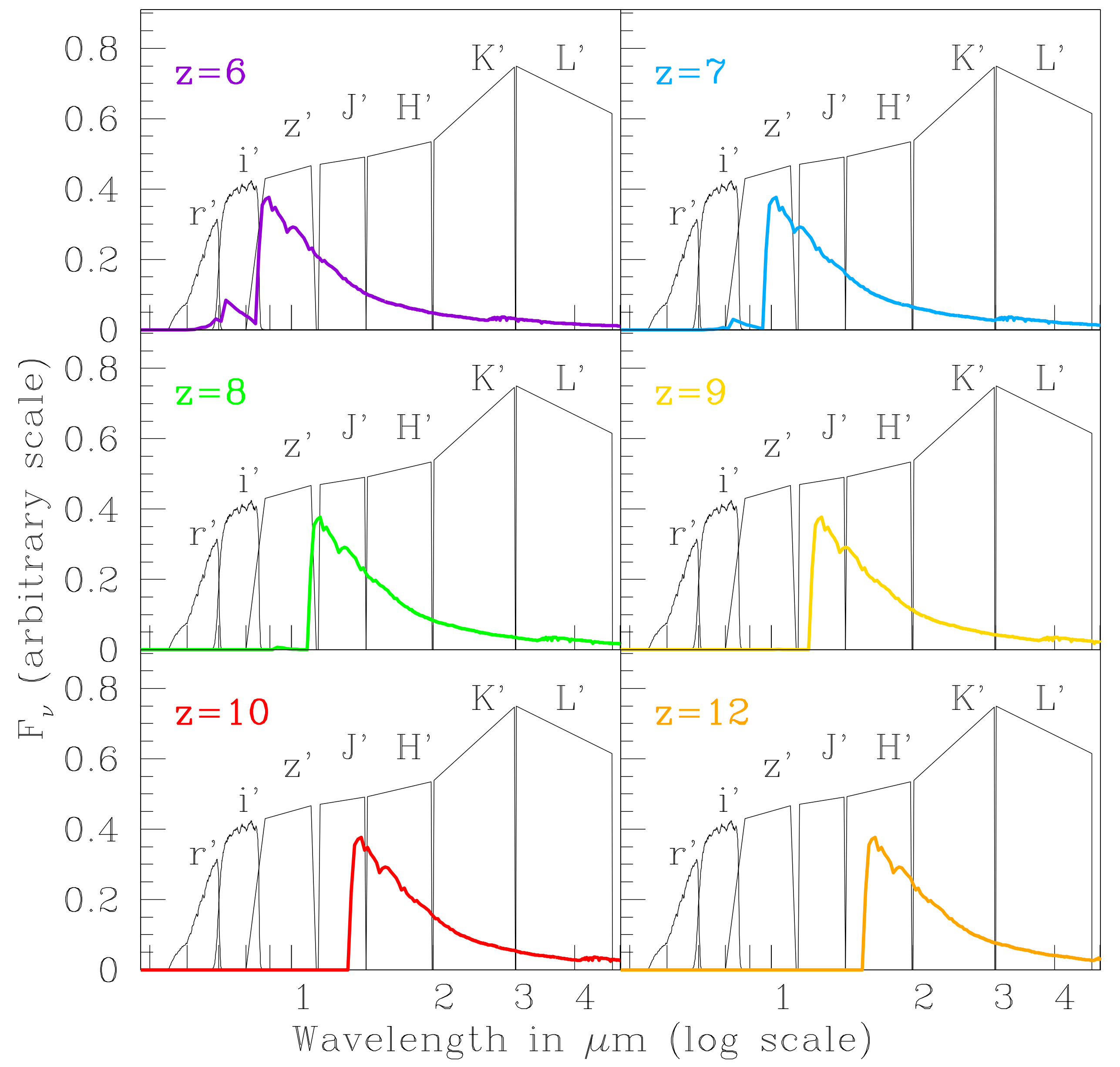
$\Longrightarrow$ First Light & Reionization occurred between these extremes:

- (1) Instantaneous at $z\simeq11.1\pm1.1$ (τ=0.089±0.013), or, more likely:
- (2) Inhomogeneous & drawn out: starting at $z\gtrsim20$, peaking at $z\lesssim11$, ending at $z\simeq7$. The implications for HST and JWST are:

- HST/ACS has covered $z\lesssim6$, and WFC3 is covering $z\lesssim$7–9.
- For First Light & Reionization, JWST will survey $z\simeq8$ to $z\simeq$15–20.

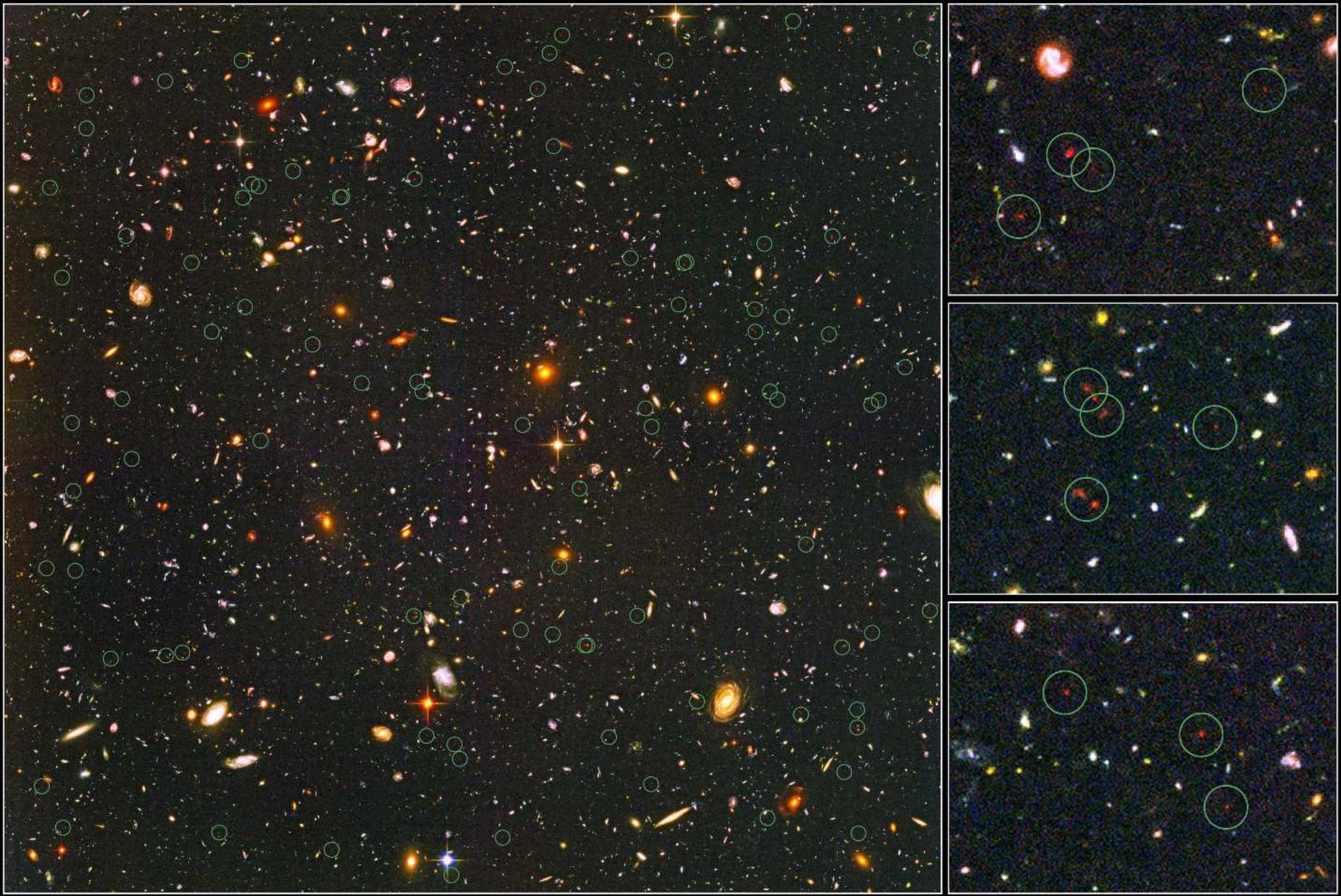
Question: If Planck-τ ↓ $\lesssim$0.08 (TBD), then how many reionizers will JWST see at $z\simeq$10–20?

(4) How will JWST measure First Light & Reionization?



- Can't beat redshift: to see First Light, must observe near–mid IR.

⇒ This is why JWST needs NIRCam at 0.8–5 μm and MIRI at 5–28 μm.

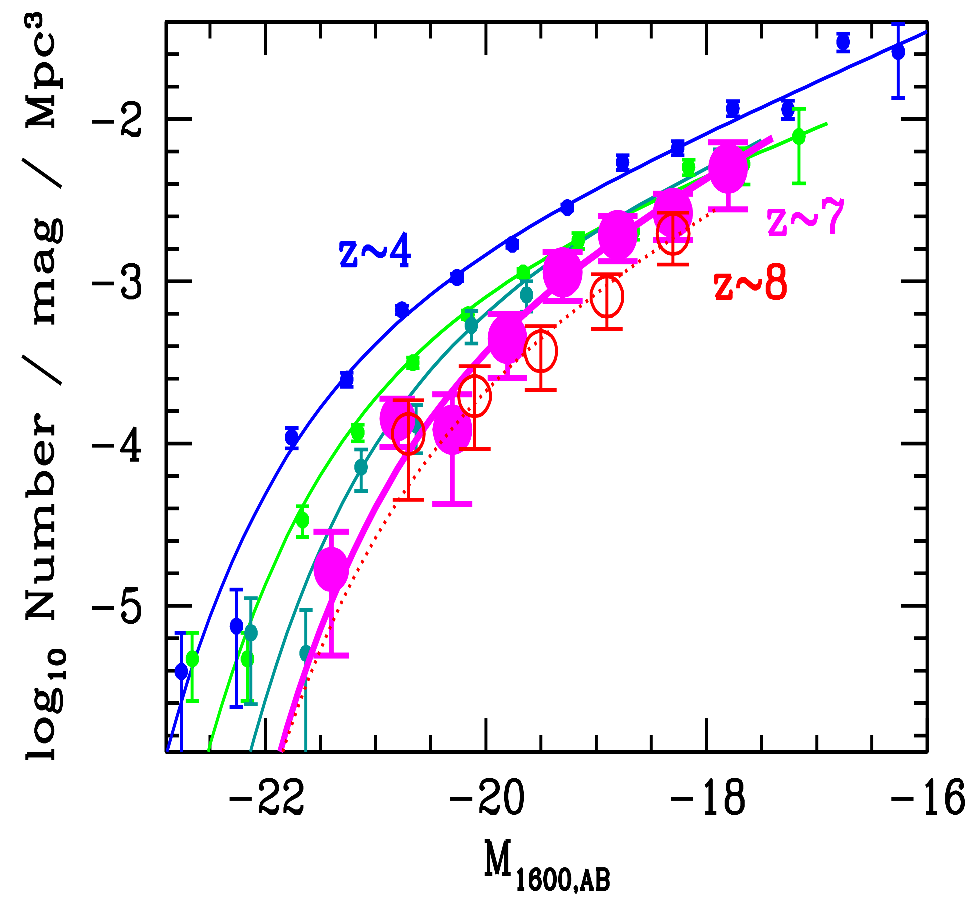


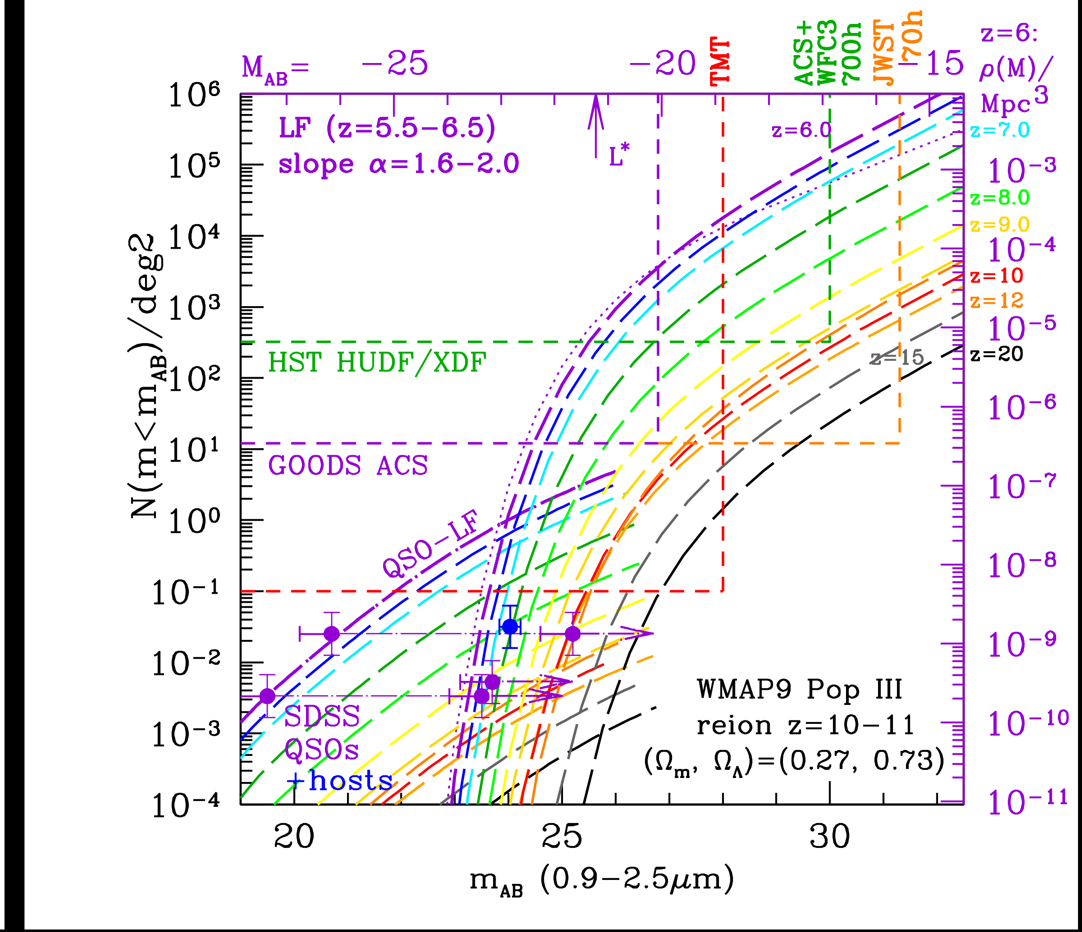
Distant Galaxies in the Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, R. Windhorst (Arizona State University) and H. Yan (Spitzer Science Center, Caltech)

STScI-PRC04-28

Hubble UltraDeep Field: Dwarf galaxies at z≃6 (age≃1 Gyr; Yan & Windhorst 2004), many confirmed by spectra at z≃6 (Malhotra et al. 2005).



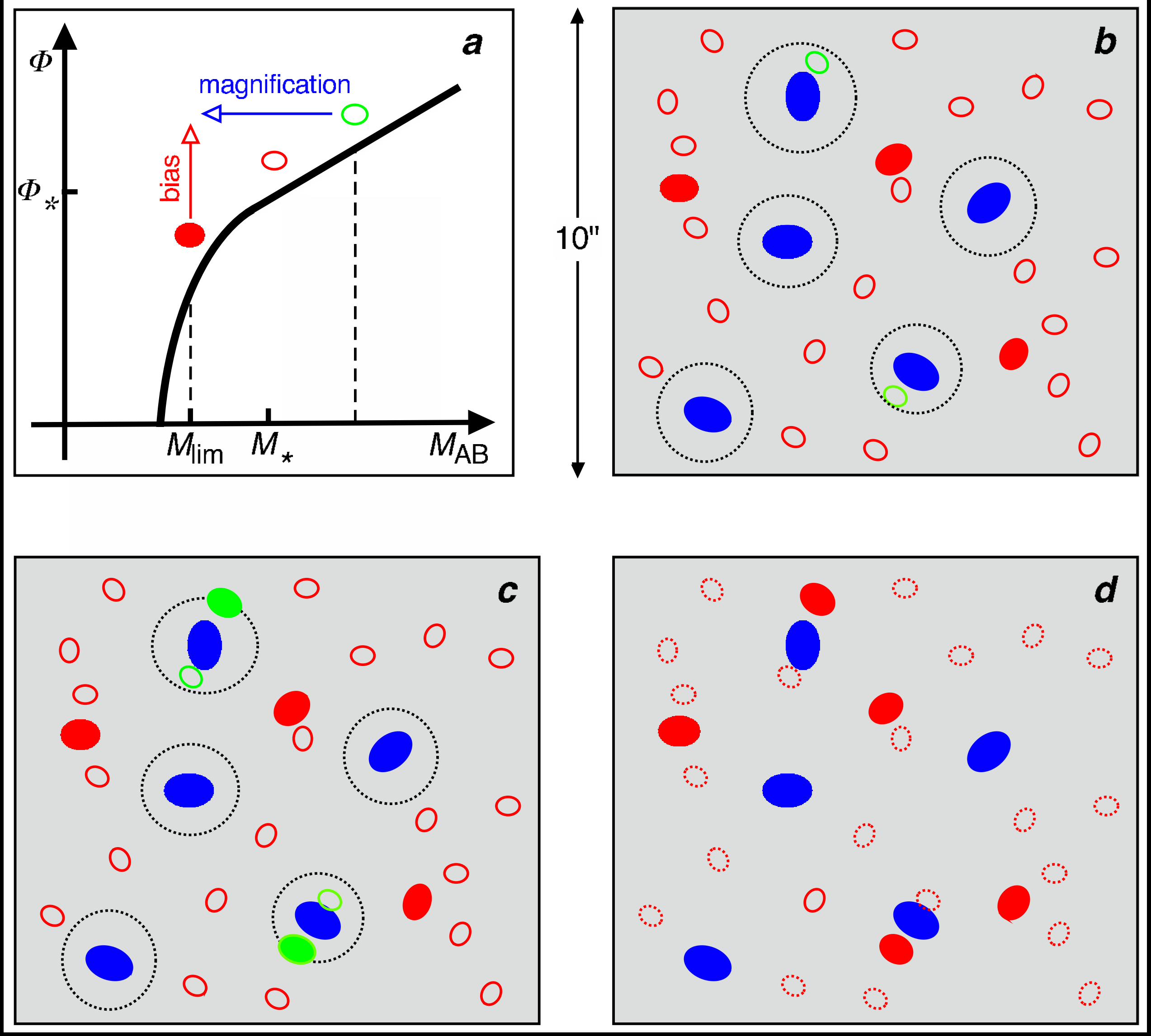


- Objects at $z\gtrsim9$ are rare (Bouwens$^+$ 12; Trenti,$^+$ 10; Yan$^+$ 10), since volume elt is small, and JWST samples brighter part of LF. JWST needs its sensitivity/aperture (A), field-of-view (Ω), and λ-range (0.7-29 μm).

- With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch and detect the first star-forming objects.

- JWST Coronagraphs can also trace super-massive black-holes as faint quasars in young galaxies: JWST needs 2.0μm diffraction limit for this.

(4) Gravitational Lensing to see the Reionizing population at z$\gtrsim$8.



Hard to see the forest for the trees in the first 0.5 Gyrs?:

- Foreground galaxies (z$\simeq$1–2 or age$\simeq$3–6 Gyr) may gravitationally lens or amplify galaxies at z$\gtrsim$8–10 (cosmic age$\lesssim$0.5 Gyr; Wyithe et al. 2011).
- This could change the landscape for JWST observing strategies.
- Strength of effect at z$\gtrsim$8–10 depends on how fast M^* declines with z.

Two fundamental limitations may determine ultimate JWST image depth:

(1) Cannot-see-the-forest-for-the-trees effect [Natural Confusion limit]: Background objects blend into foreground neighbors because of their own diameter $\Rightarrow$ Need multi-$\boldsymbol{\lambda}$ deblending algorithms!

(2) House-of-mirrors effect ["Gravitational Confusion"]: First Light objects at z$\gtrsim$8–10 may be gravitationally lensed by foreground halos.

$\Rightarrow$ May need multi-$\boldsymbol{\lambda}$ SExtractor that works on sloped backgrounds!

$\Rightarrow$ If M*(z$\gtrsim$10)$\gtrsim$–19, may need to model entire gravitational foreground.

- Proper JWST 2.0μm PSF and straylight specs essential to handle this.

(5) Conclusions

(1) HST set stage to measure galaxy assembly in the last 12.7-13.0 Gyrs.

- Today's Hubble sequence formed 7–10 Gyrs ago.
- Most $z \simeq 6$ QSO host galaxies faint (dusty?), with 1 exception: $L >> L^*$.

(2) JWST passed Preliminary & Critical Design Reviews in 2008 & 2010.

Management replan in 2010-2011. No technical showstoppers thus far:

- More than 75% of JWST H/W built or in fab, & meets/exceeds specs.

(3) JWST is designed to map the epochs of First Light, Reionization, and Galaxy Assembly & SMBH-growth in detail. JWST will determine:

- Formation and evolution of the first star-clusters after 0.2 Gyr.
- How dwarf galaxies formed and reionized the Universe after 1 Gyr.

(4) JWST will have a major impact on astrophysics this decade:

- IR sequel to HST after 2018: Training the next generation researchers.
- JWST will define the next frontier to explore: the Dark Ages at $z \gtrsim 20$.

SPARE CHARTS

- References and other sources of material shown:

http://www.asu.edu/clas/hst/www/jwst/ [Talk, Movie, Java-tool]

http://www.asu.edu/clas/hst/www/ahah/ [Hubble at Hyperspeed Java–tool]

http://www.asu.edu/clas/hst/www/jwst/clickonHUDF/ [Clickable HUDF map]

http://www.jwst.nasa.gov/ & http://www.stsci.edu/jwst/

http://ircamera.as.arizona.edu/nircam/

http://ircamera.as.arizona.edu/MIRI/

http://www.stsci.edu/jwst/instruments/nirspec/

http://www.stsci.edu/jwst/instruments/fgs

Gardner, J. P., et al. 2006, Space Science Reviews, 123, 485–606

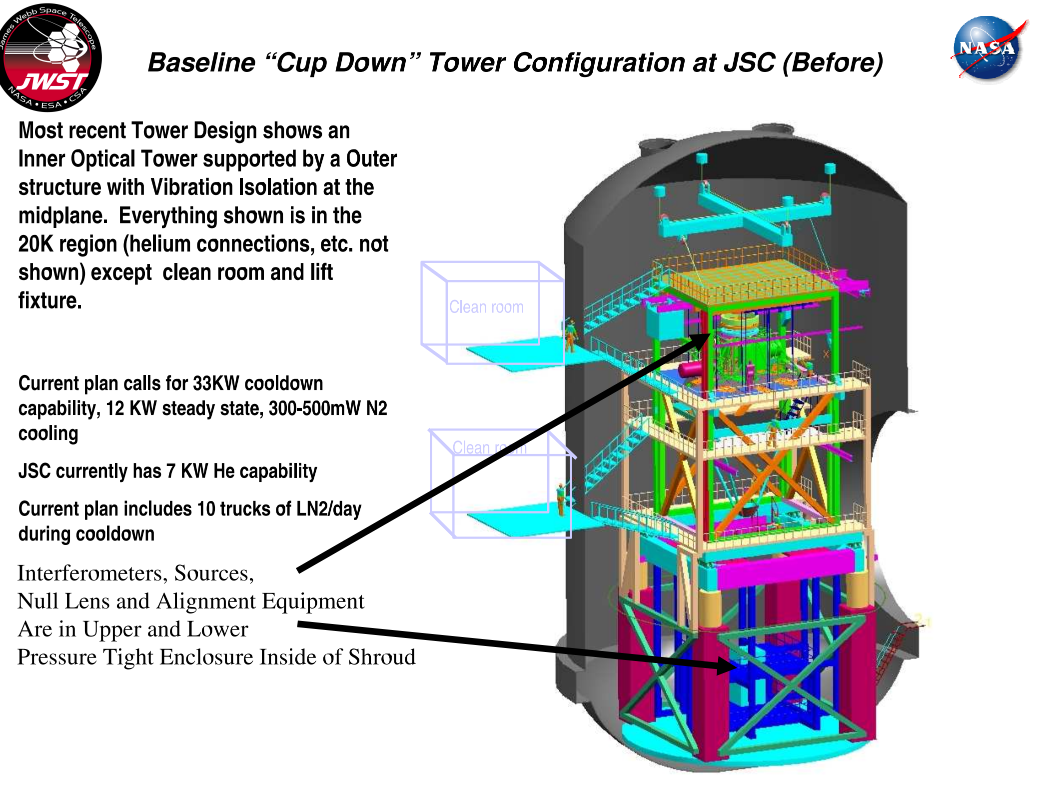
Mather, J., & Stockman, H. 2000, Proc. SPIE Vol. 4013, 2

Windhorst, R., et al. 2008, Advances in Space Research, 41, 1965

Windhorst, R., et al., 2011, ApJS, 193, 27 (astro-ph/1005.2776).

Northrop Grumman Expertise in Space Deployable Systems

- Over 45 years experience in the design, manufacture, integration, verification and flight operation of spacecraft deployables
- 100% mission success rate, comprising over 640 deployable systems with over 2000 elements



Baseline "Cup Down" Tower Configuration at JSC (Before)

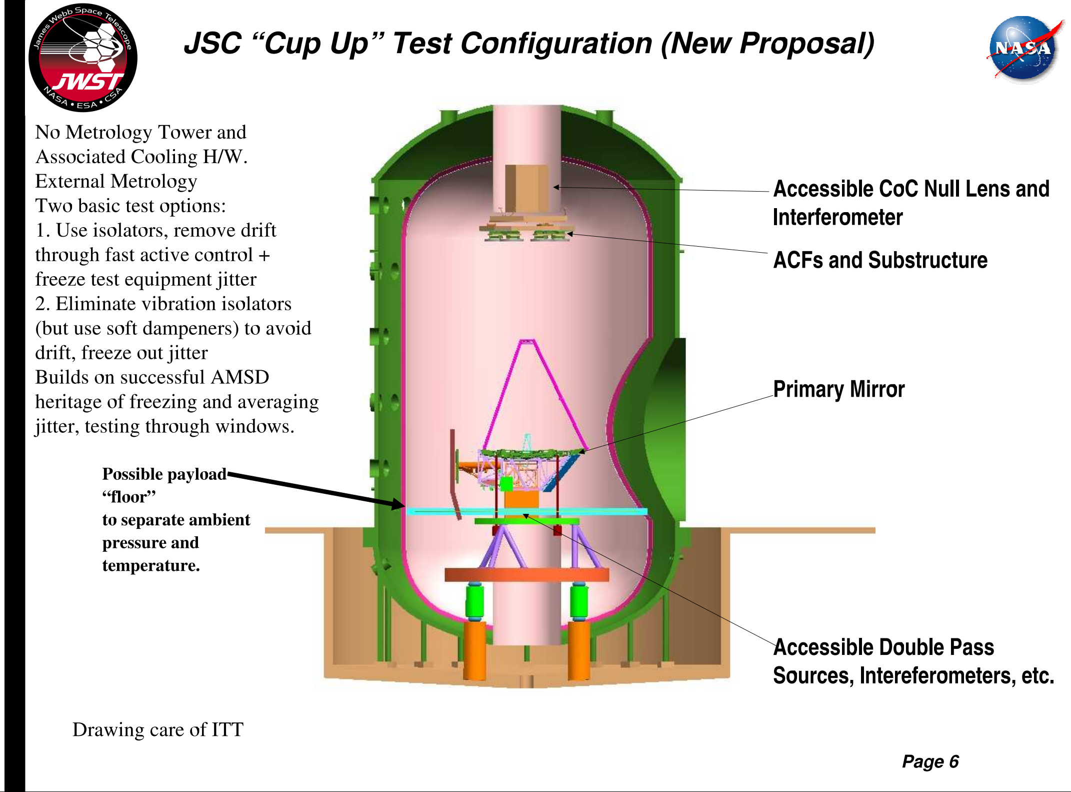
Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

Current plan calls for 33KW cooldown capability, 12 KW steady state, 300-500mW N2 cooling

JSC currently has 7 KW He capability

Current plan includes 10 trucks of LN2/day during cooldown

Interferometers, Sources, Null Lens and Alignment Equipment Are in Upper and Lower Pressure Tight Enclosure Inside of Shroud



JSC "Cup Up" Test Configuration (New Proposal)

No Metrology Tower and Associated Cooling H/W.
External Metrology
Two basic test options:
1. Use isolators, remove drift through fast active control + freeze test equipment jitter
2. Eliminate vibration isolators (but use soft dampeners) to avoid drift, freeze out jitter
Builds on successful AMSD heritage of freezing and averaging jitter, testing through windows.

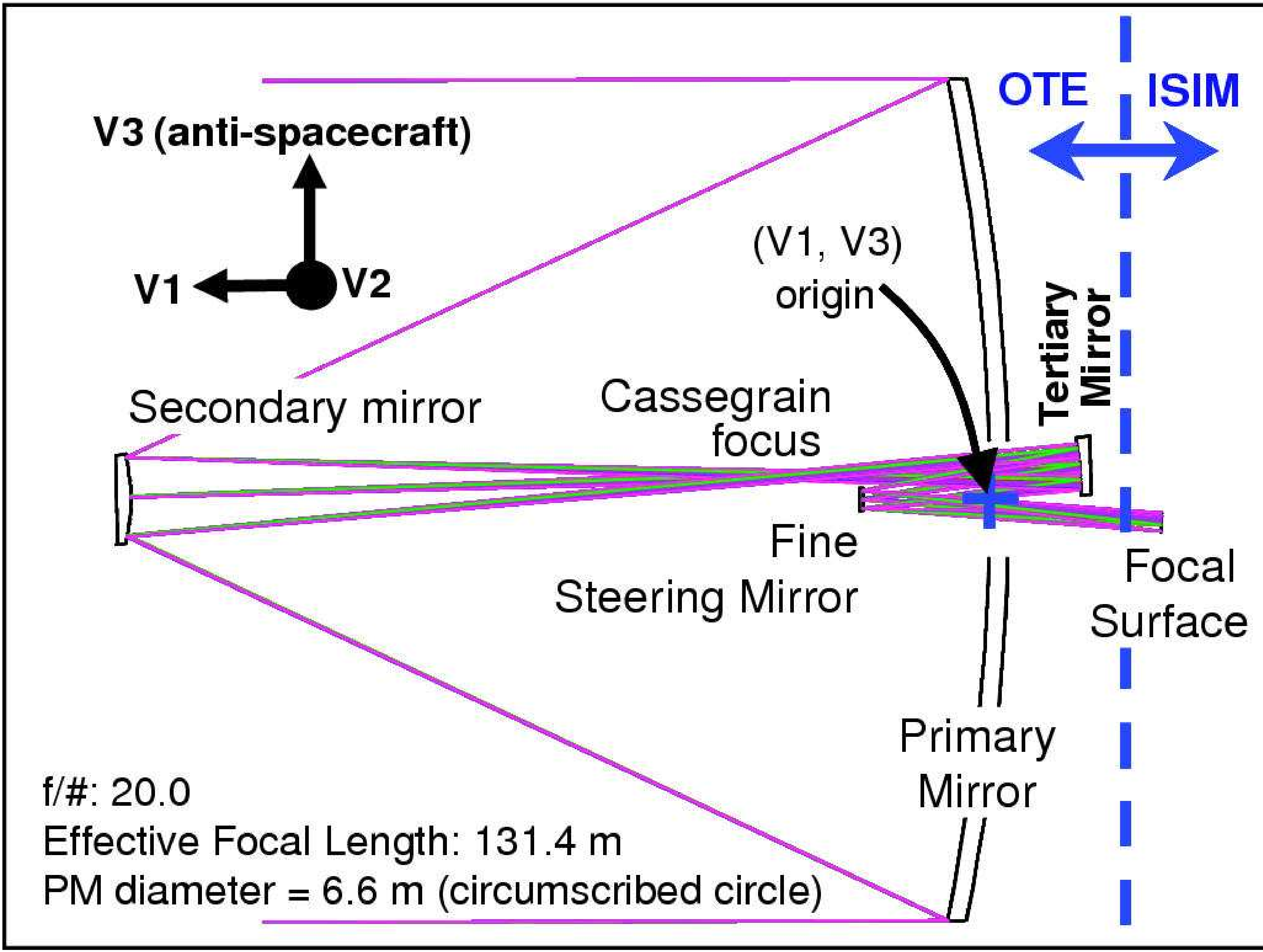
Possible payload "floor" to separate ambient pressure and temperature.

Drawing care of ITT

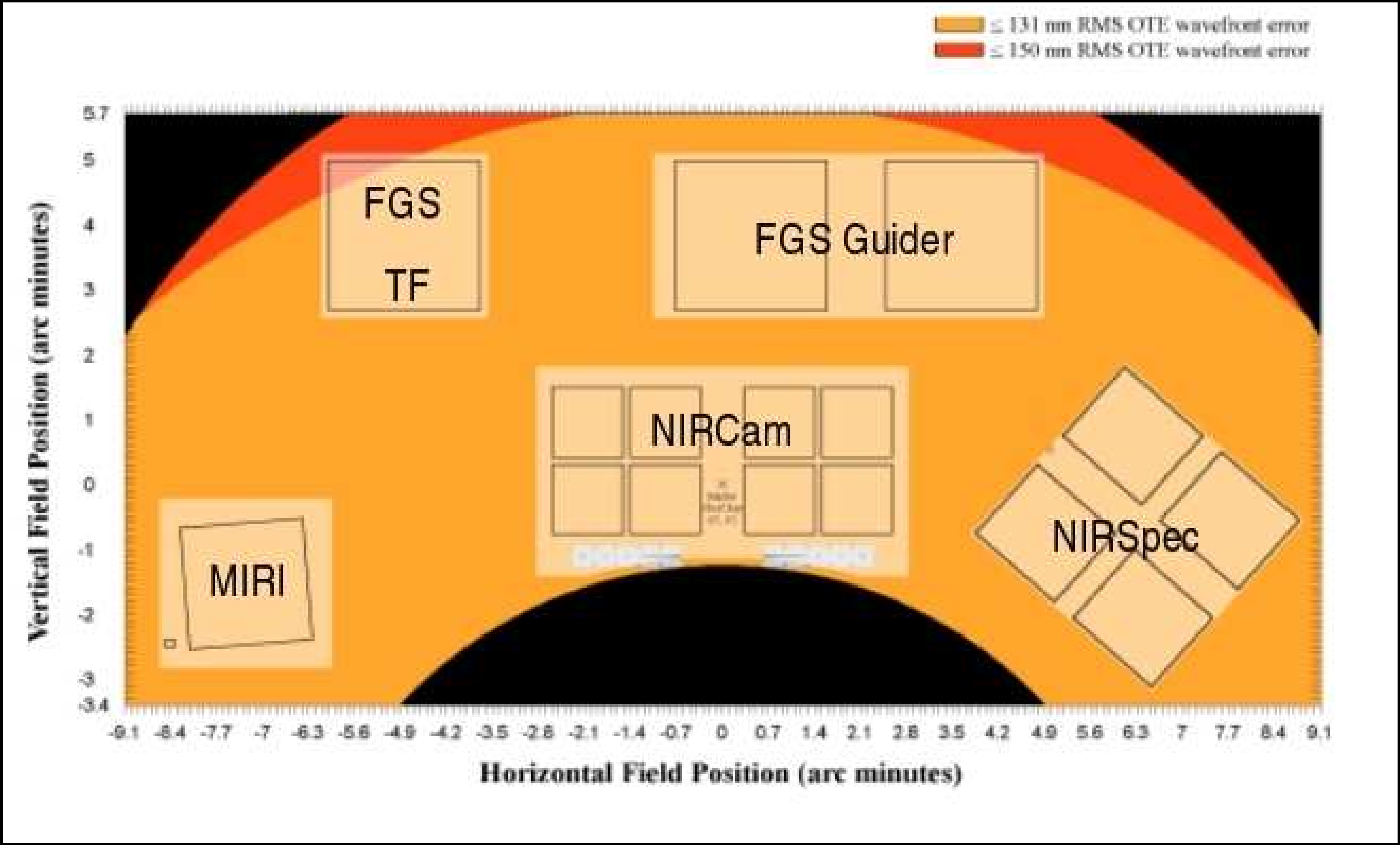
Page 6

JWST underwent several significant replans and risk-reduction schemes:

- $\lesssim$2003: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0 μm performance specs (kept 2.0 μm).
- 2005: Simplification of thermal vacuum tests: cup-up, not cup-down.
- 2006: All critical technology at Technical Readiness Level 6 (TRL-6).
- 2007: Further simplification of sun-shield and end-to-end testing.
- 2008: Passes Mission Preliminary Design & Non-advocate Reviews.
- 2010, 2011: Passes Mission Critical Design Review: Replan Int. & Testing.


OTE
ISIM
V3 (anti-spacecraft)
V1
V2
(V1, V3)
origin
Tertiary Mirror
Secondary mirror
Cassegrain focus
Fine Steering Mirror
Focal Surface
Primary Mirror
f/#: 20.0
Effective Focal Length: 131.4 m
PM diameter = 6.6 m (circumscribed circle)

• (3c) What instruments will JWST have?



All JWST instruments can in principle be used in parallel observing mode:

- Currently only being implemented for parallel *calibrations.*

One day we will need a UV-optical sequel to Hubble:

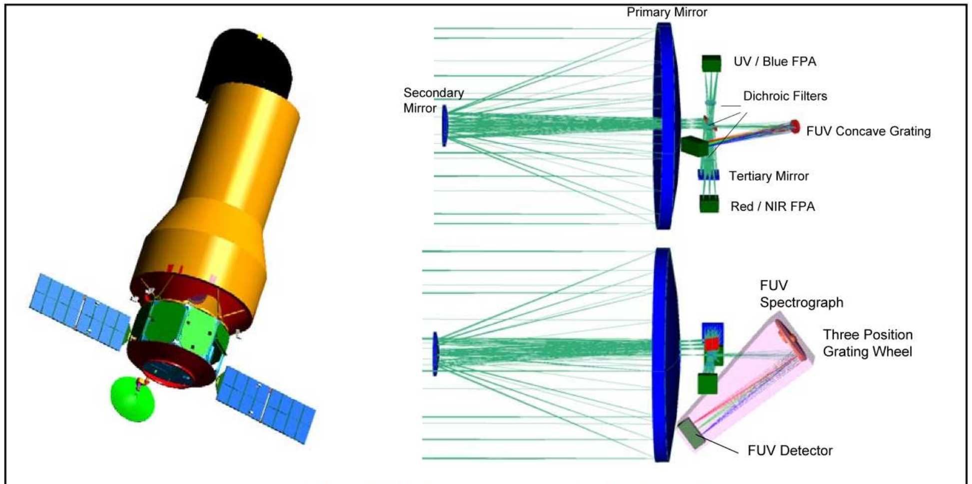
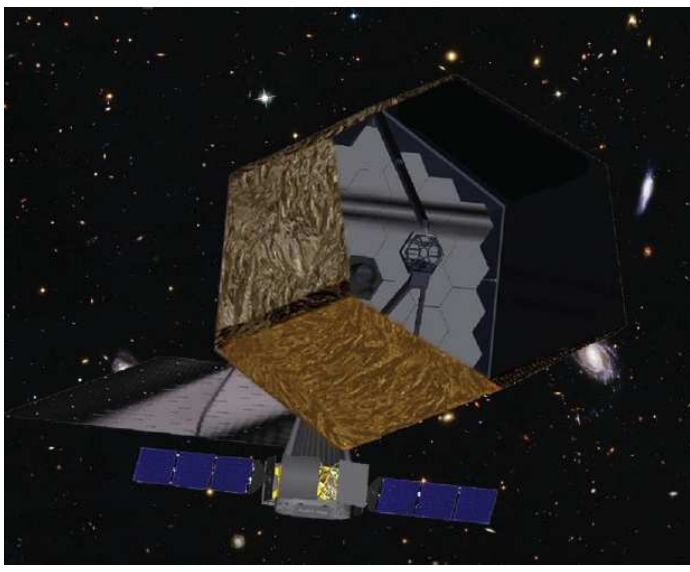


Figure 2.5.3 - *HORUS* Observatory and Optical Ray Trace



[Left] One of two spare 2.4 m NRO mirrors: one will become WFIRST.

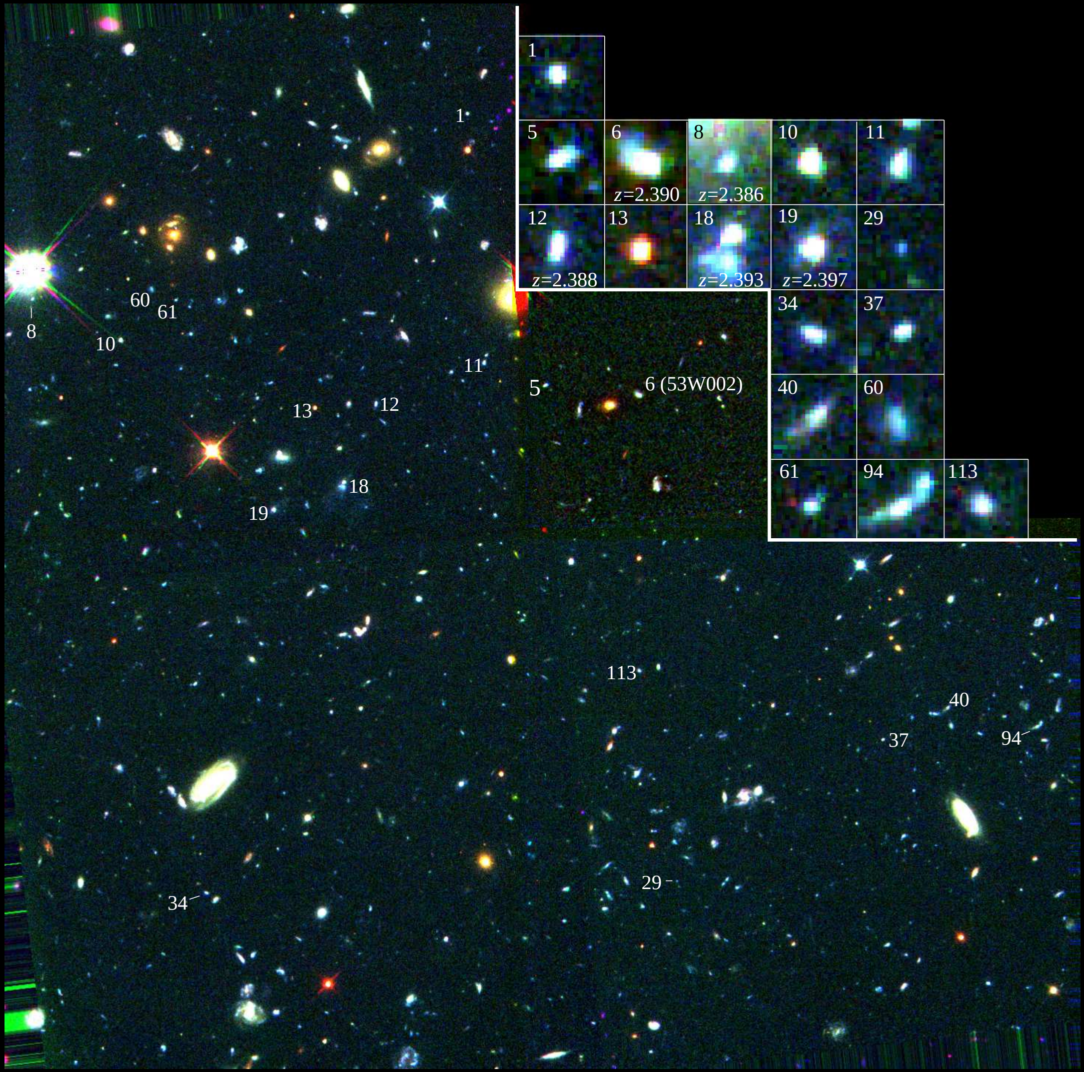
- NASA may look for partners to turn 2nd NRO into UV-opt HST sequel.

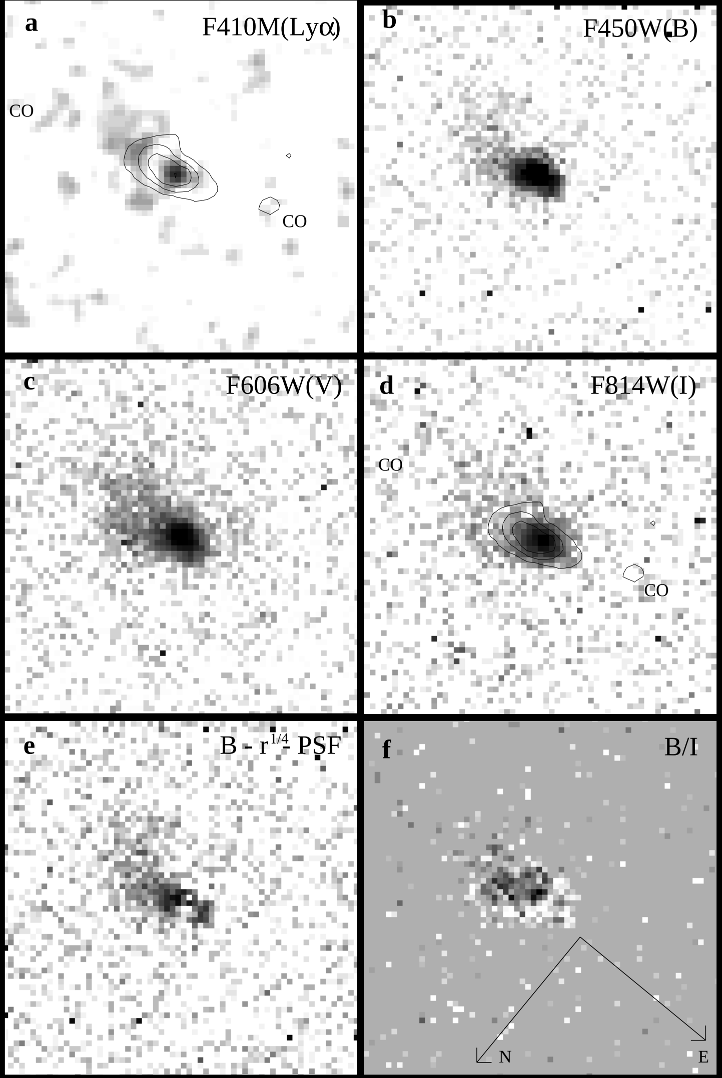
[Middle] HORUS: 3-mirror anastigmat NRO as UV-opt HST sequel.

- Can do wide-field ($\sim$0.25 deg) UV-opt $0\farcs06$ FWHM imaging to AB$\lesssim$29-30 mag, and high sensitivity (on-axis) UV-spectroscopy.

[Right] ATLAST: 8–16 m UV-opt HST sequel, with JWST heritage.

- Can do same at 9 m.a.s. FWHM routinely to AB$\lesssim$32-34 mag, [and an ATLAST-UDF to AB $\lesssim$38 mag $\sim$1 pico-Jy].



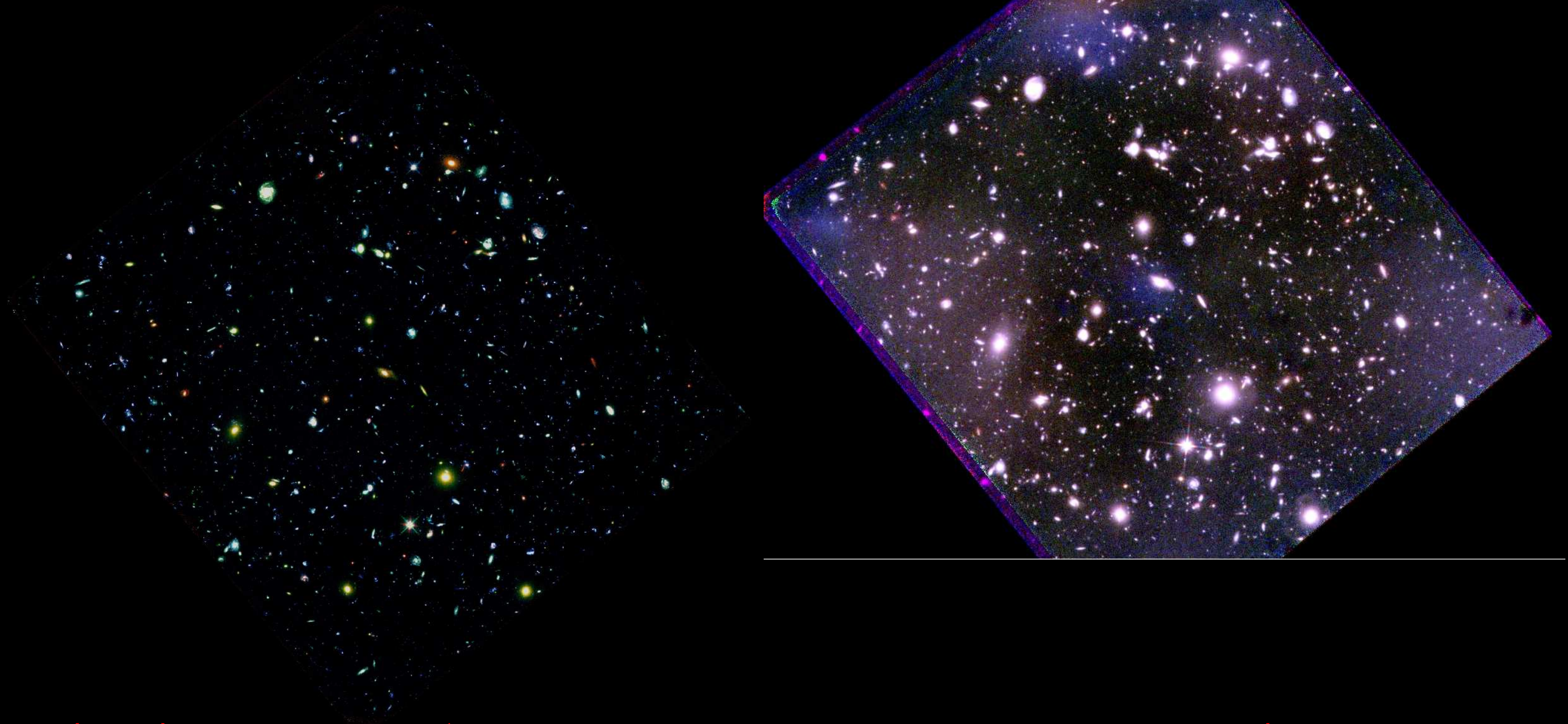


(Left): WFPC2 BVI + F410M (Lyα) on 53W002 + surrounding group of 17 z=2.39 Lyα candidates (Pascarelle et al. 1996, Nature, 383, 45).

(Right): HST/PC of radio galaxy 53W002 at z=2.390 (Windhorst et al. 1998, ApJL): stellar r$^{1/4}$-law + Lyα & blue continuum AGN-cloud.

$\Longrightarrow$ Ly escape fraction should be measured *outside* LBGs with outflows!

- JWST can measure AGN hosts 4–6 mag fainter in restframe UV-Opt to z$\lesssim$20

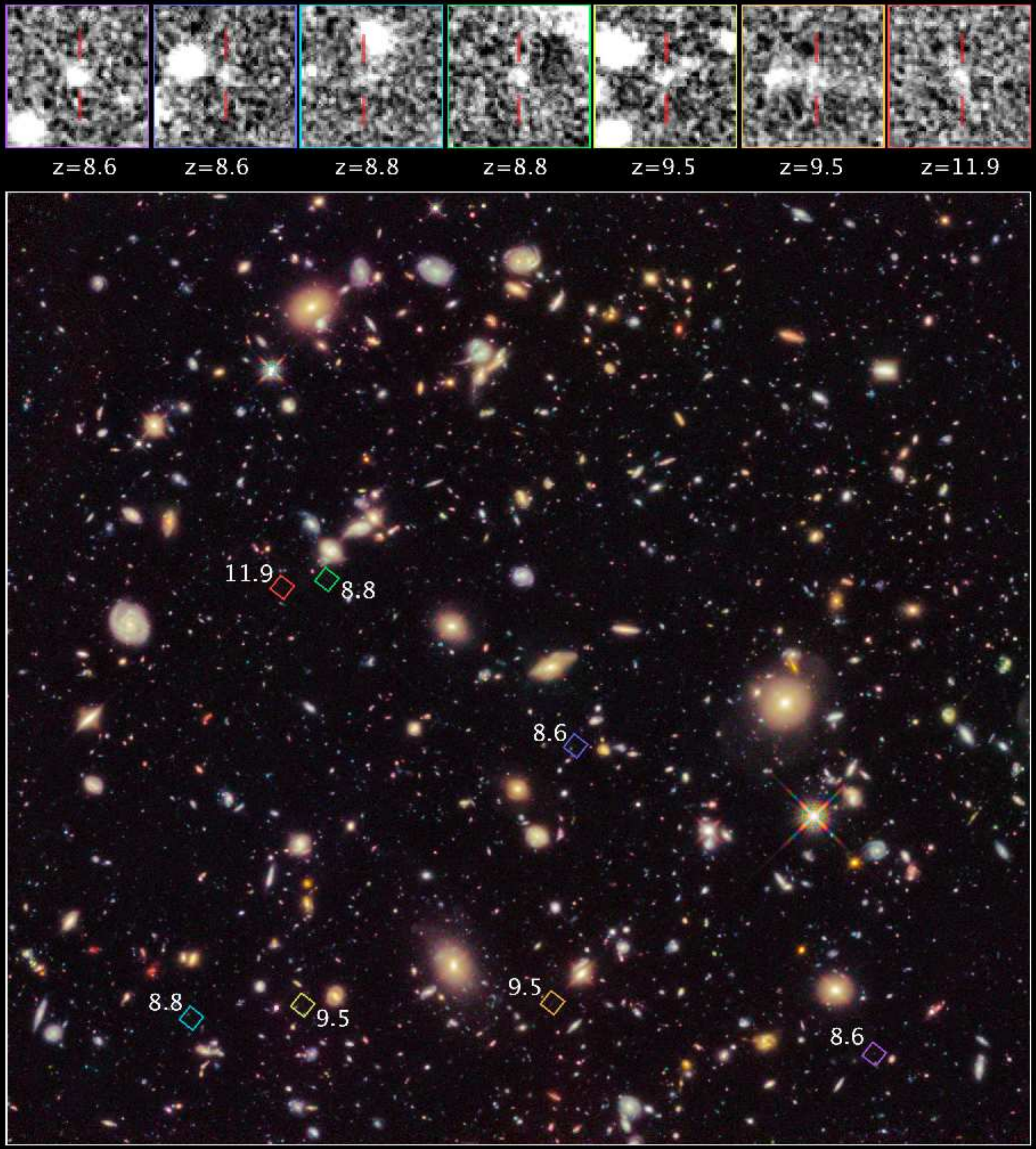


(Left) 128-hr HST/WFC3 IR-mosaic in HUDF at 1–1.6μm (YJH filters; Bouwens et al 2010, Yan et al. 2010; +85-hr by R. Ellis in 09/2012).

(Right) Same WFC3 IR-mosaic, but stretched to $\lesssim 10^{-3}$ of Zodical sky!

- The CLOSED-TUBE HST has residual low-level systematics: Imperfect removal of detector artifacts, flat-fielding errors, and/or faint straylight.

$\Rightarrow$ The open JWST architecture needs very good baffling and rogue path mitigation to do ultradeep JWST fields (JUDF's) to 10^{-4} of sky.

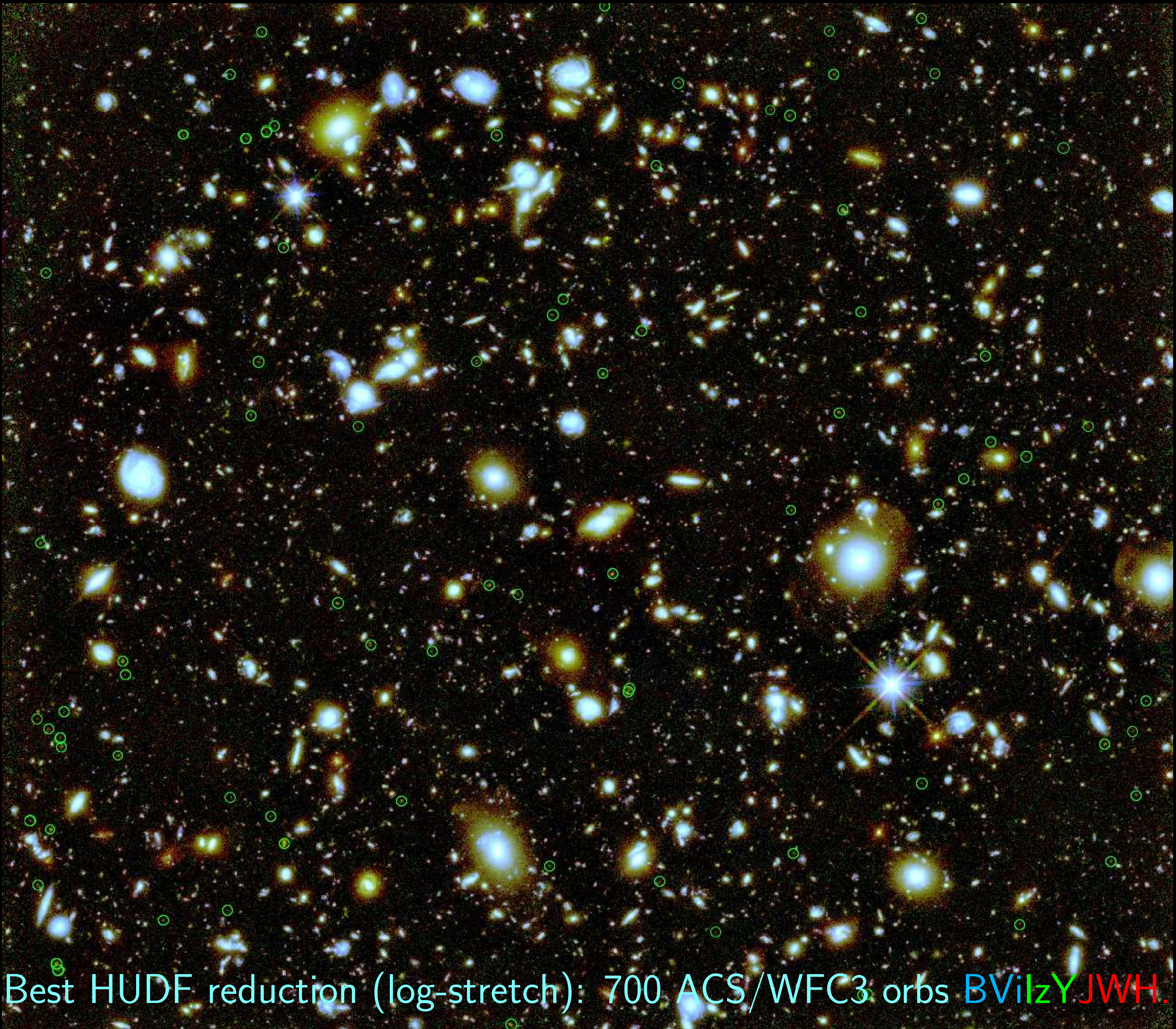


Hubble Ultra Deep Field 2012

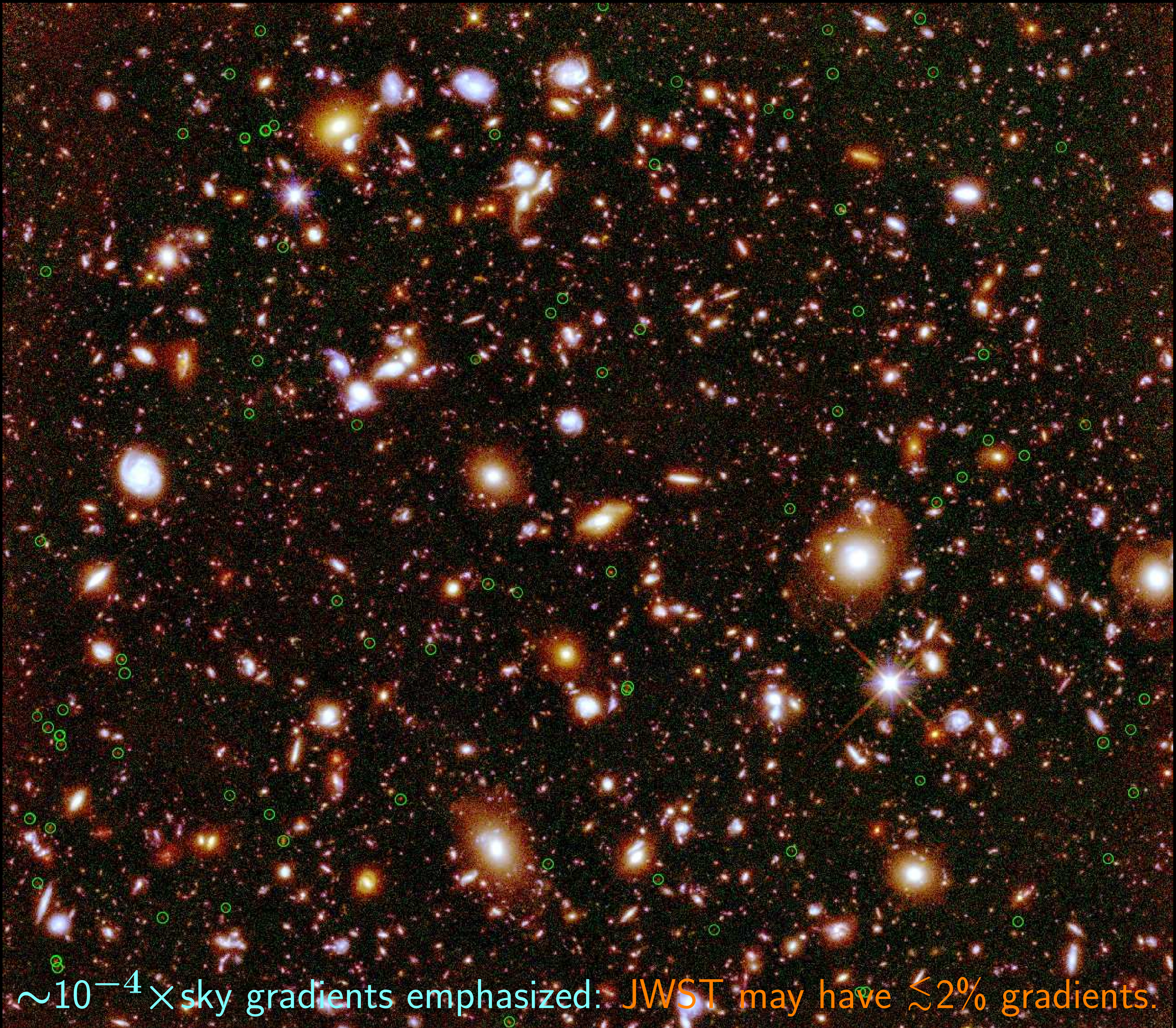
Hubble Space Telescope WFC3/IR

NASA and ESA

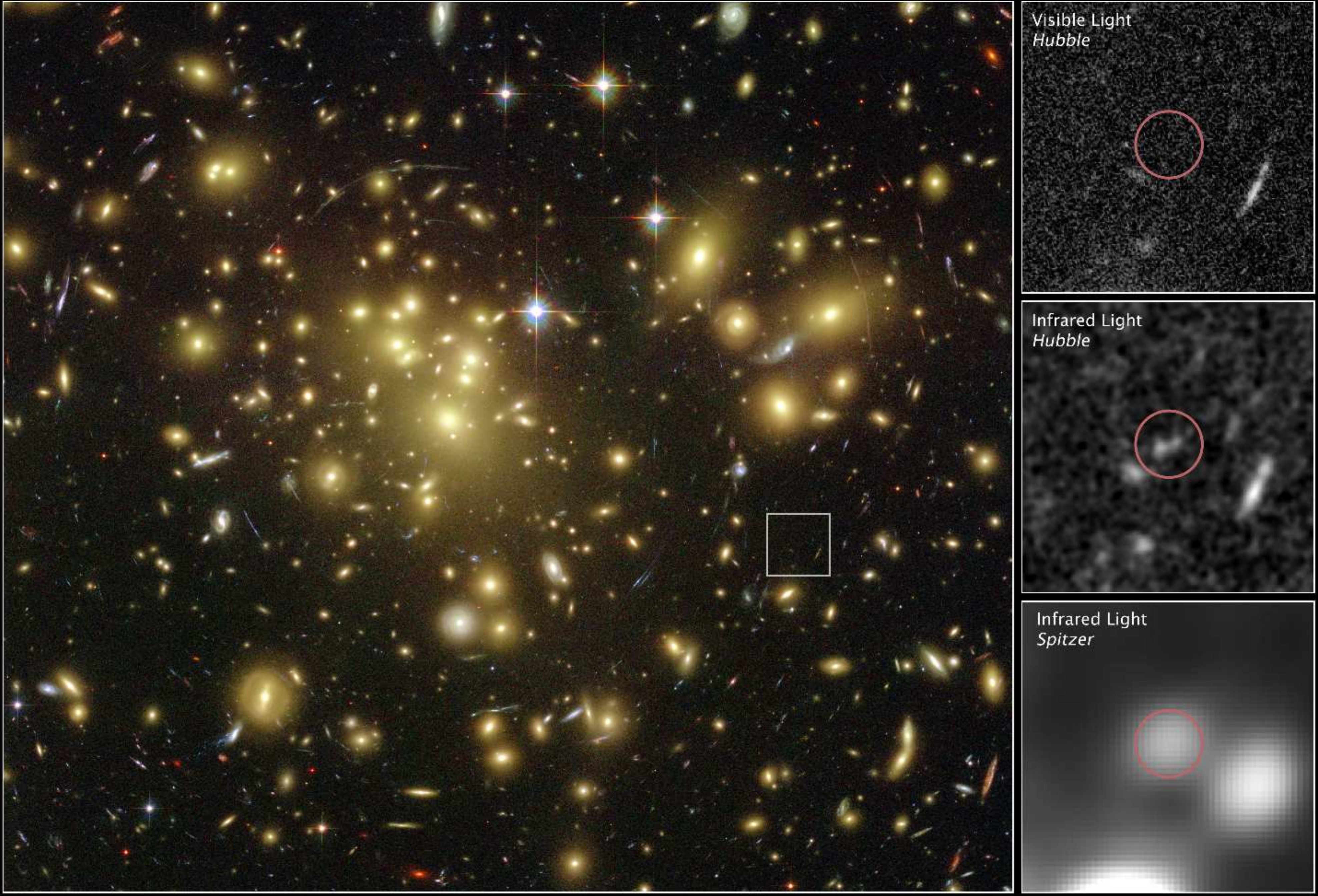
STScI-PRC12-48a



Best HUDF reduction (log-stretch): 700 ACS/WFC3 orbs BViIzYJWH.



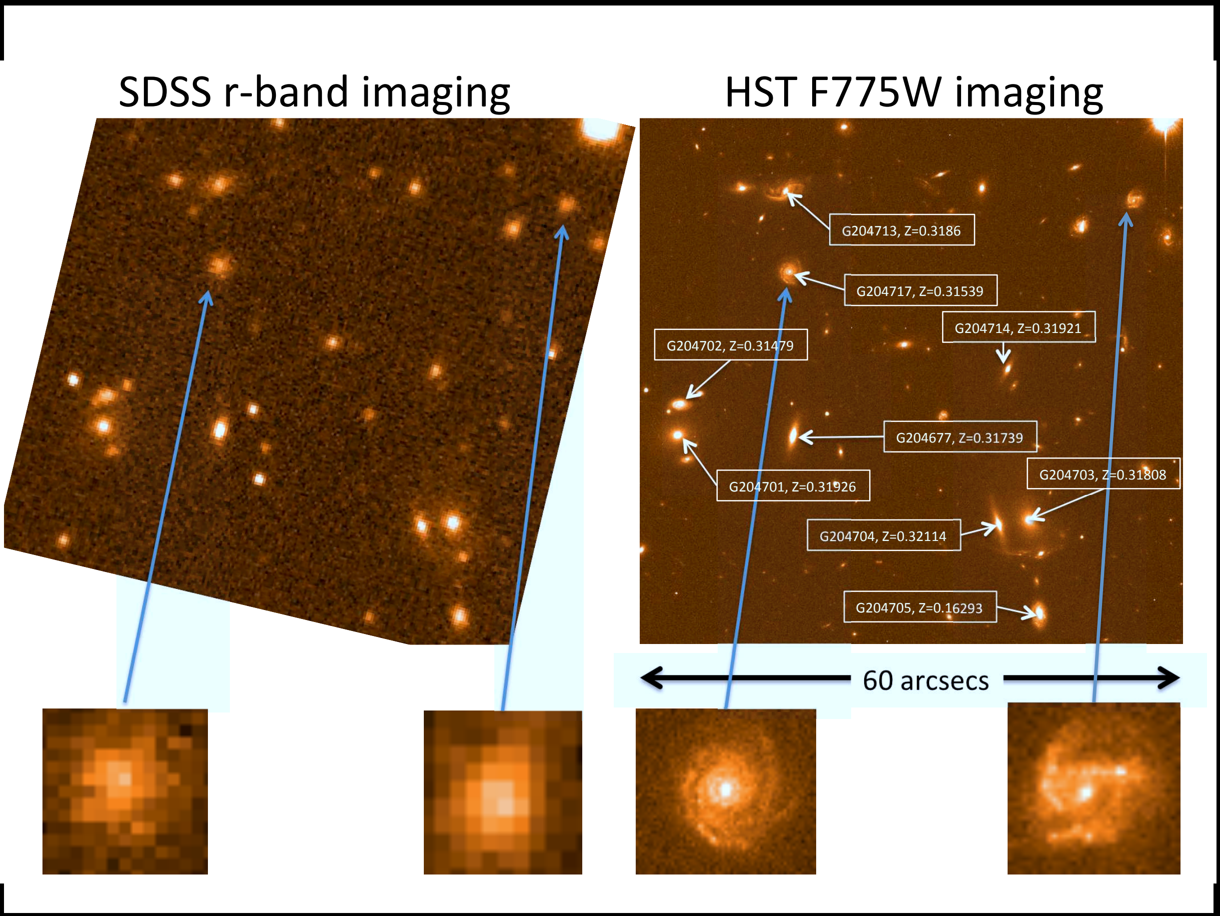
$\sim 10^{-4} \times$ sky gradients emphasized: JWST may have $\lesssim 2\%$ gradients.

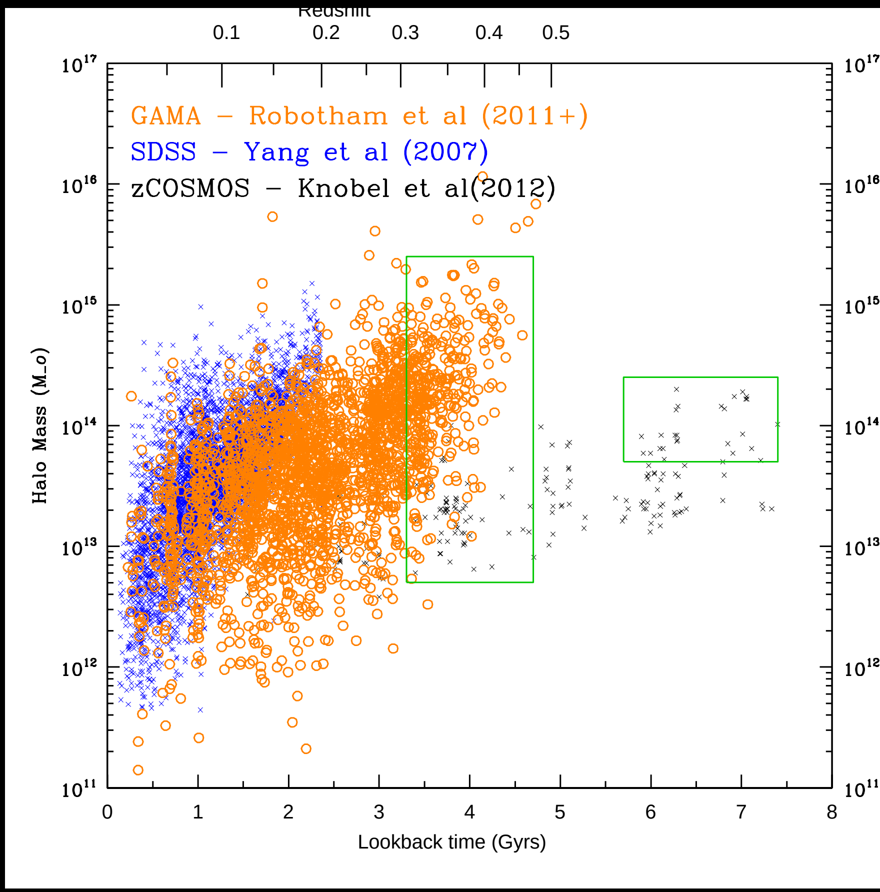


Distant Gravitationally Lensed Galaxy ▪ Galaxy Cluster Abell 1689
Hubble Space Telescope ▪ ACS/WFC NICMOS

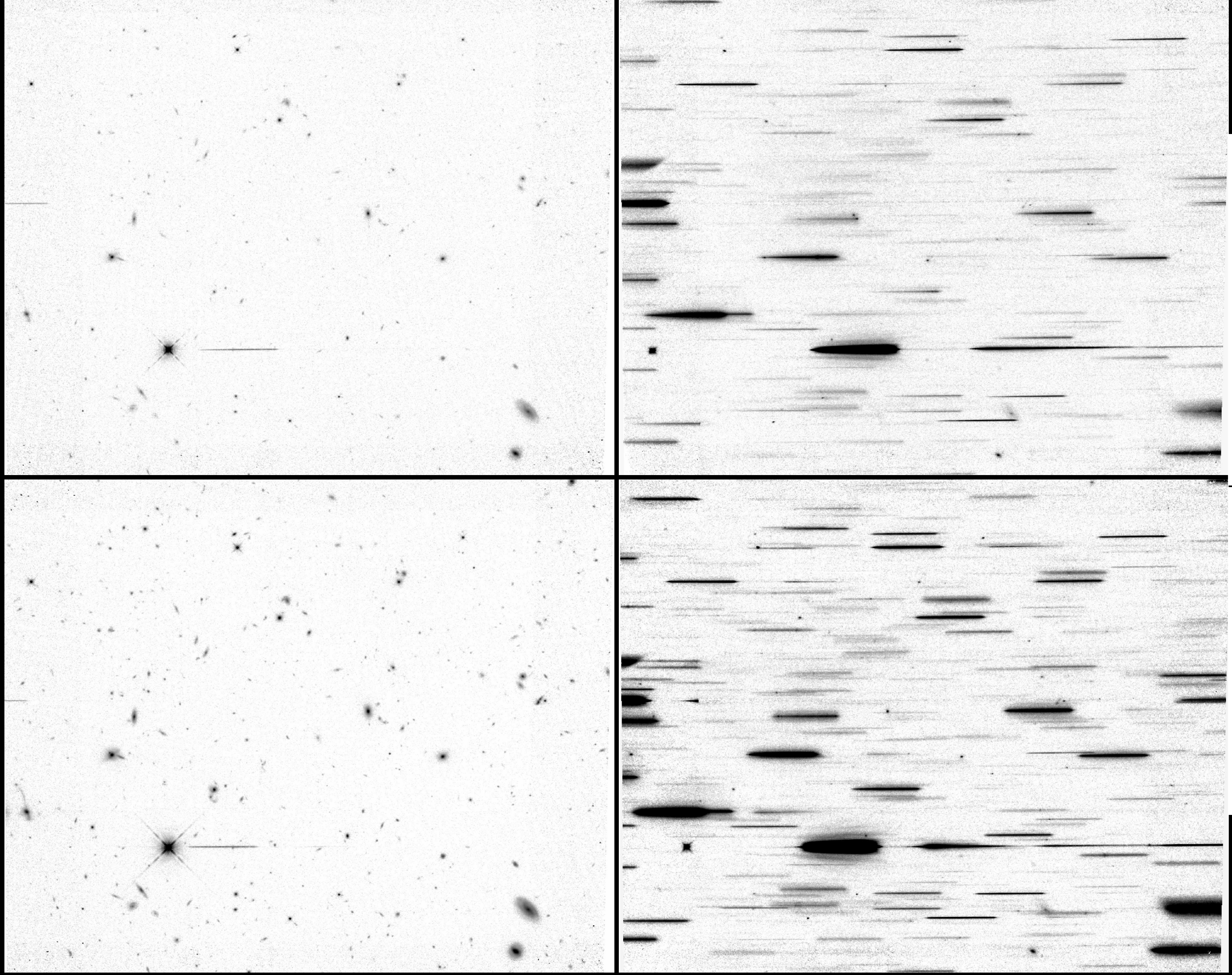
NASA, ESA, and L. Bradley (JHU), R. Bouwens (UCSC), H. Ford (JHU), and G. Illingworth (UCSC) STScI-PRC08-08a

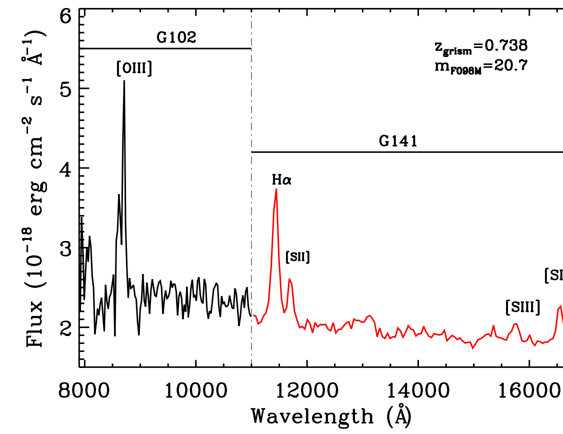
$\lesssim$2% of JWST-sky straylight gradients may be hard to separate from ICL.

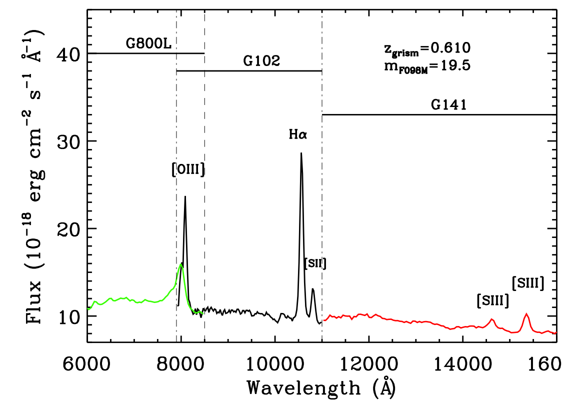




- (Left) Select the most massive known galaxy groups from GAMA at $z \gtrsim 0.35$ as gravitational lensing-bias targets for JWST studies at $z \gtrsim 2$-15.
- In rich clusters, it may be much harder to separate intra-cluster light (ICL) from out-of-field or rogue path straylight in ultradeep JWST images.
- (Right) The most massive ($\sim 10^{15}\ M_\odot$) GAMA groups at $z \gtrsim 0.4$ have a $\sim 16\times$ higher lensing cross section for $z \simeq 3$–15 candidates than the most massive COSMOS groups ($\sim 10^{14}\ M_\odot$) at $z \sim 0.75$ (R. Barone-Nugent, priv. comm) — group compactness is critical here.





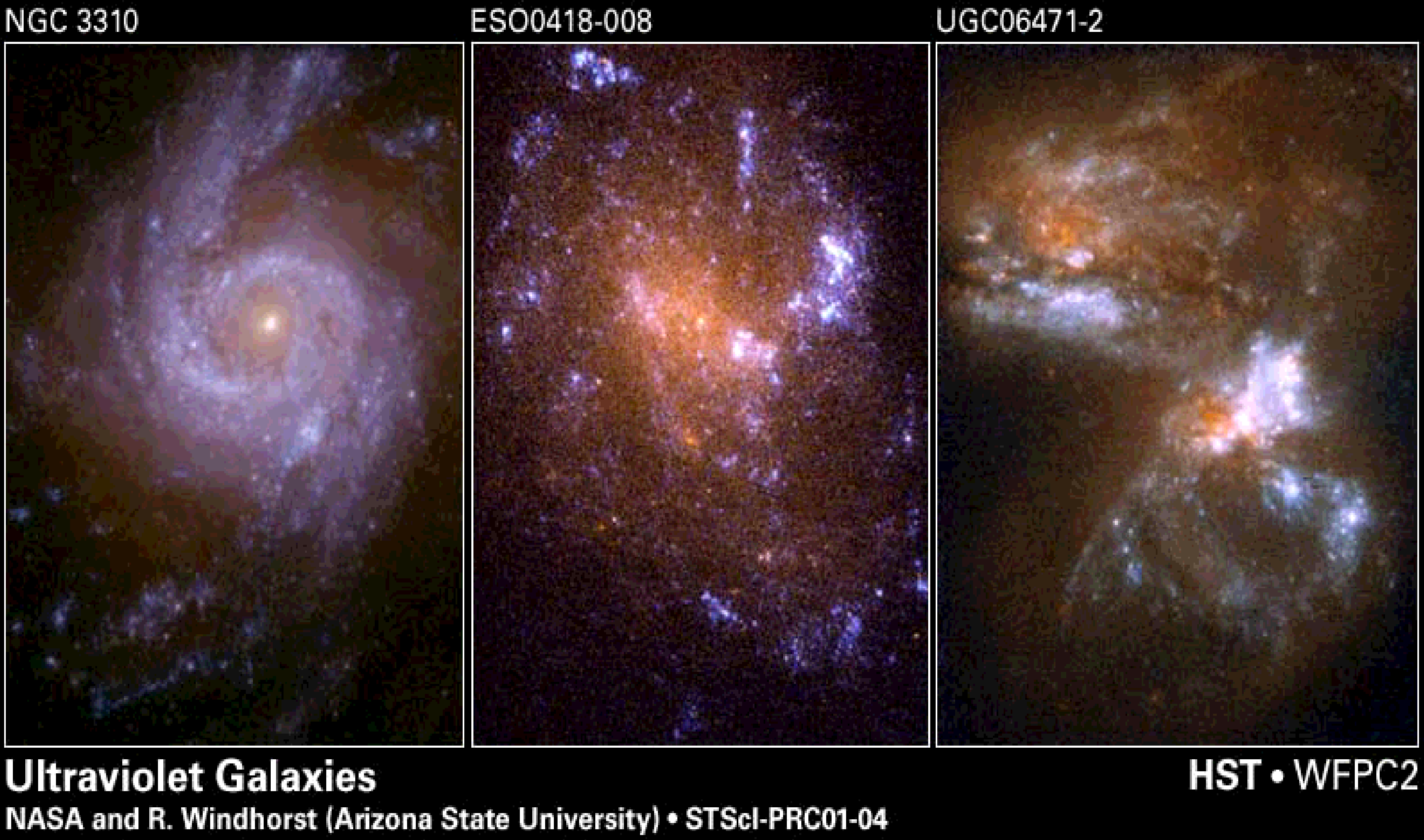


HST/WFC3 G102 & G141 grism spectra in GOODS-S ERS (Straughn^{+} 2010)

IR grism spectra from space: unprecedented new opportunities in astrophysics.

- JWST will provide near-IR grism spectra to AB$\lesssim$29 mag from 2–5.0 μm.

(4b) Predicted Galaxy Appearance for JWST at redshifts z≃1–15

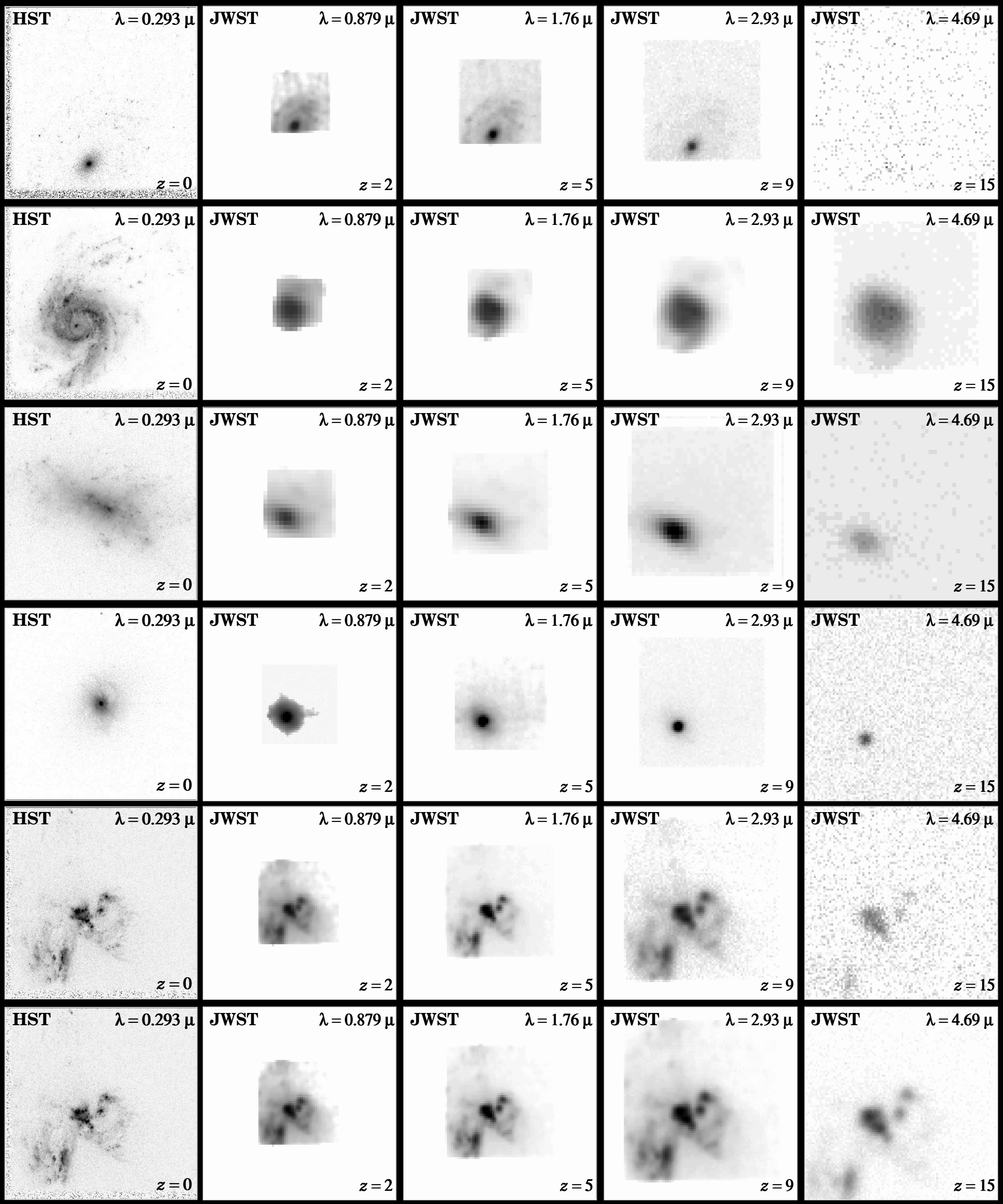


- The rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often significant dust imprinted (Mager-Taylor et al. 2005).

- High-resolution HST ultraviolet images are benchmarks for comparison with very high redshift galaxies seen by JWST.

(4b) Predicted Galaxy Appearance for JWST at redshifts z≃1–15

HST z=0 JWST z=2 z=5 z=9 z=15



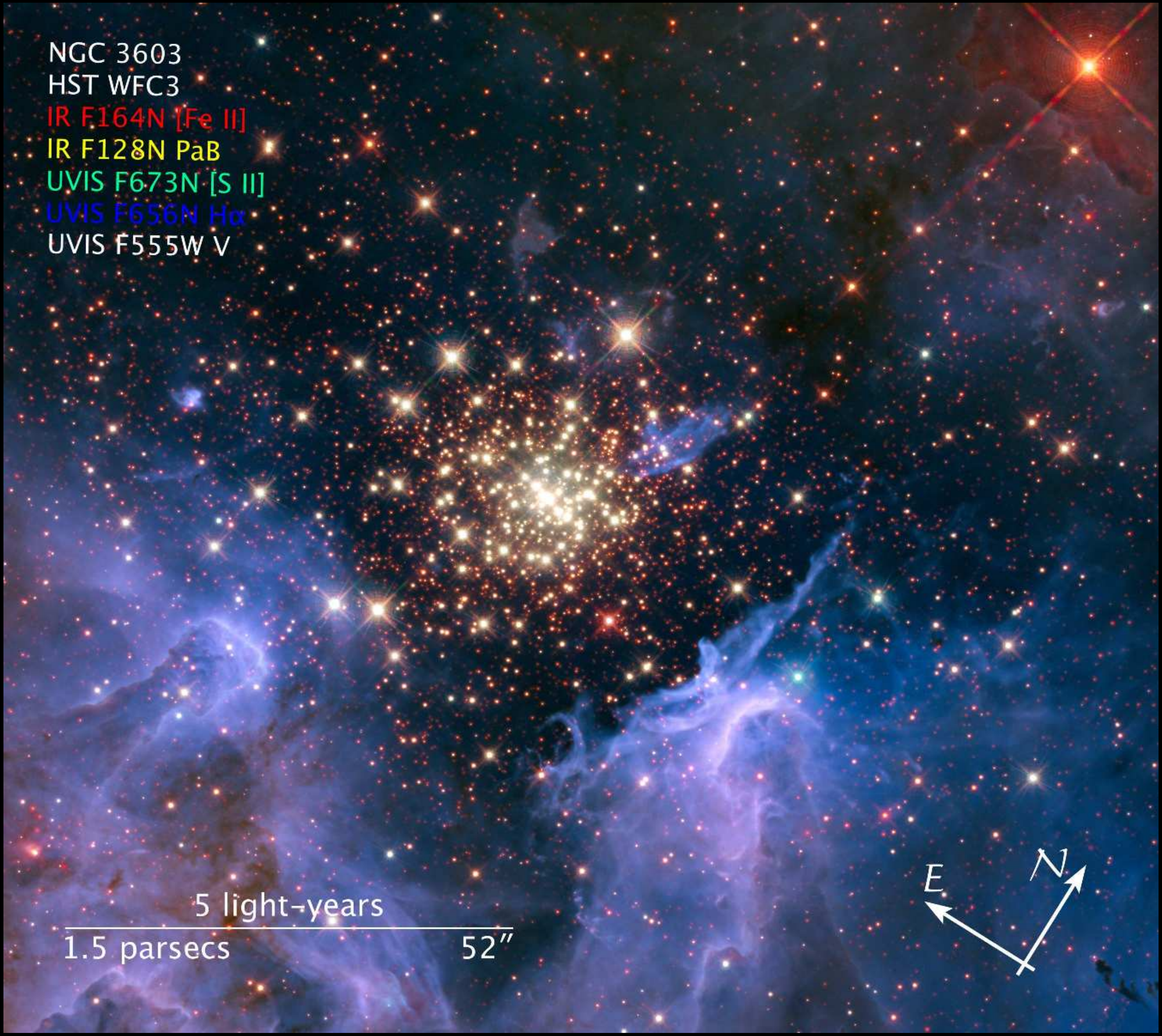
With Hubble UV-optical images as benchmarks, JWST can measure the evolution of galaxy structure & physical properties over a wide range of cosmic time:

- (1) Most spiral disks will dim away at high redshift, but most formed at z$\lesssim$1–2.

Visible to JWST at very high z are:

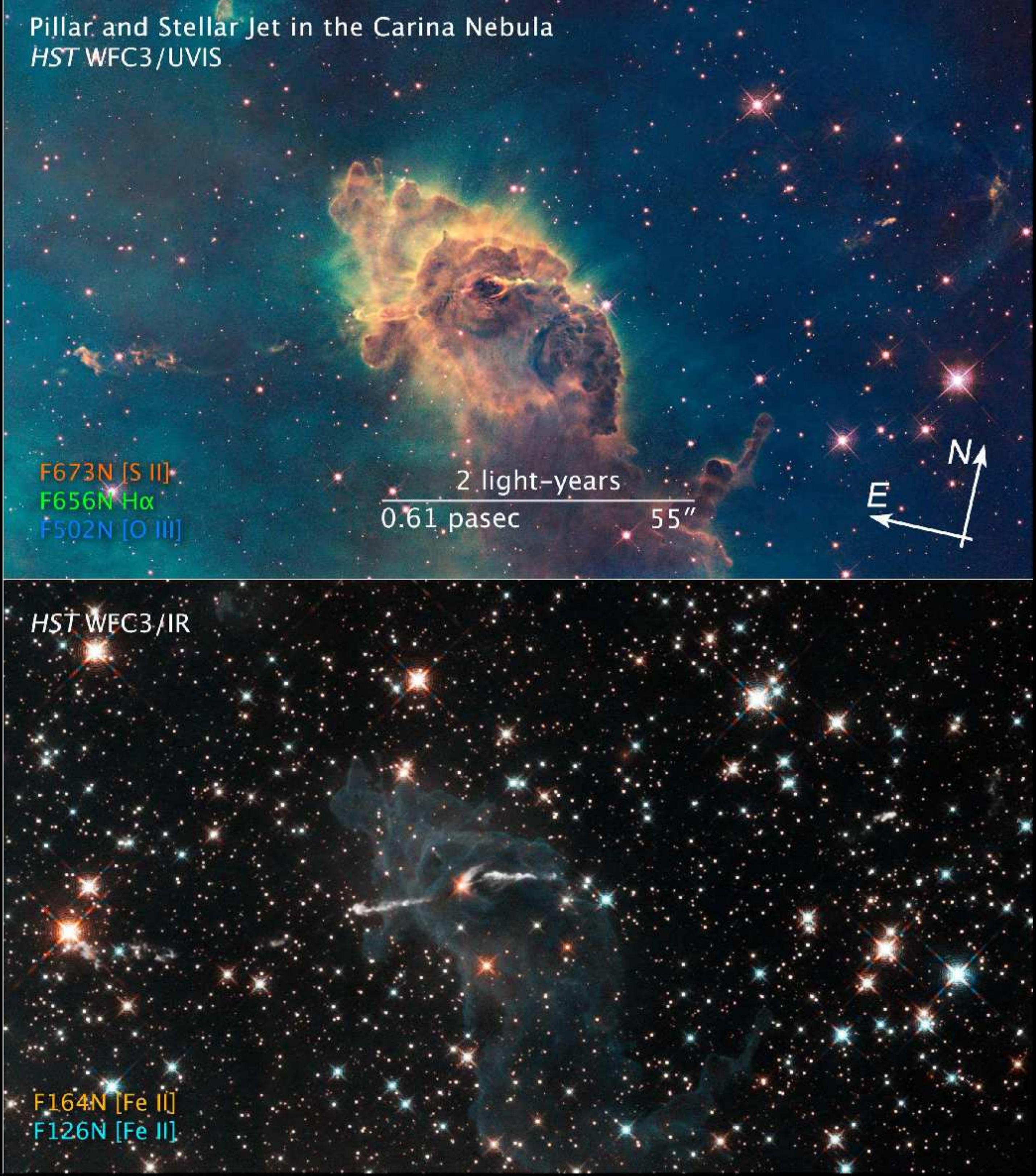
- (2) Compact star-forming objects (dwarf galaxies).
- (3) Point sources (QSOs).
- (4) Compact mergers & train-wrecks.

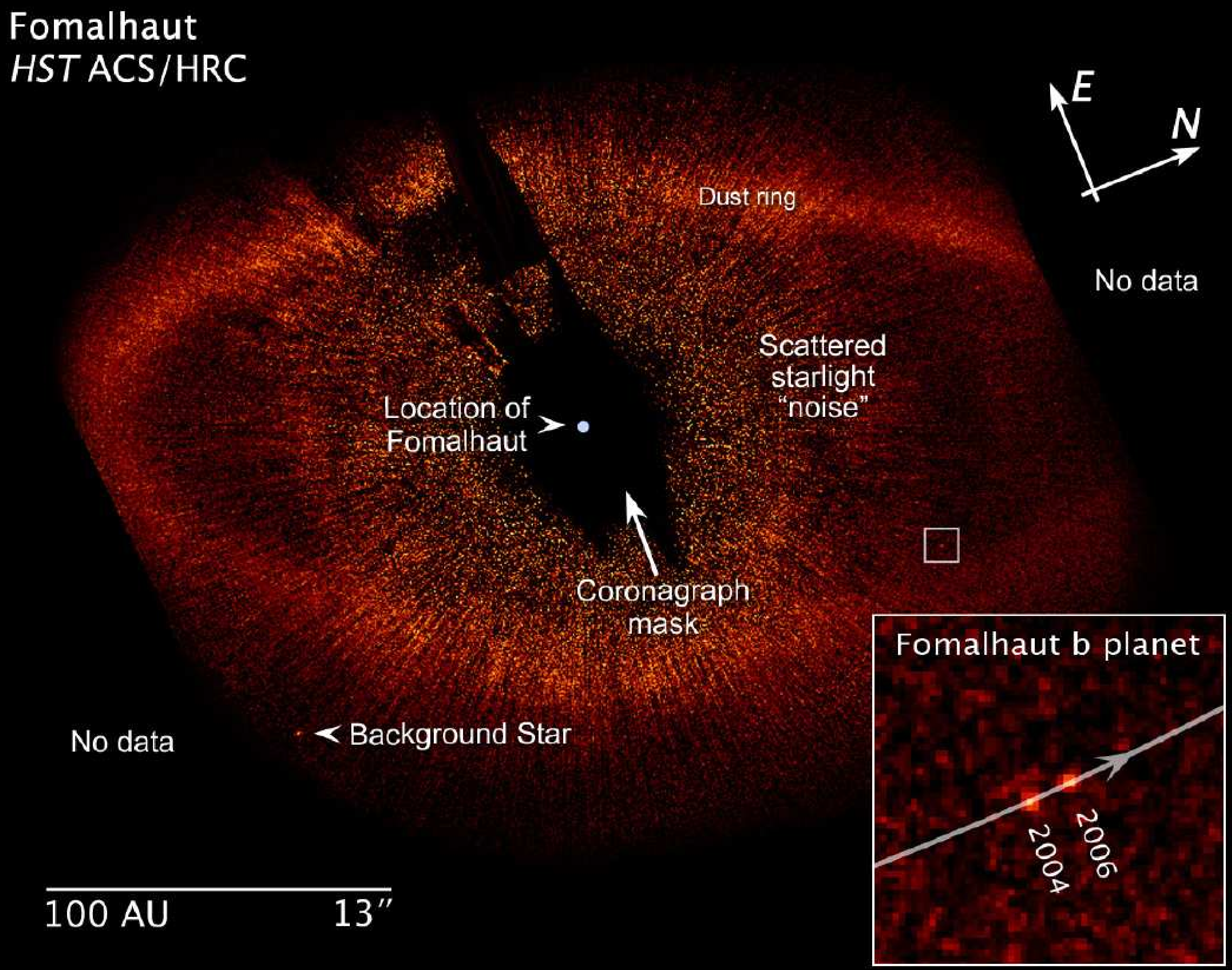
(6) How can JWST measure Star-Formation and Earth-like exoplanets?



NGC 3603: Young star-cluster triggering star-birth in "Pillars of Creation"

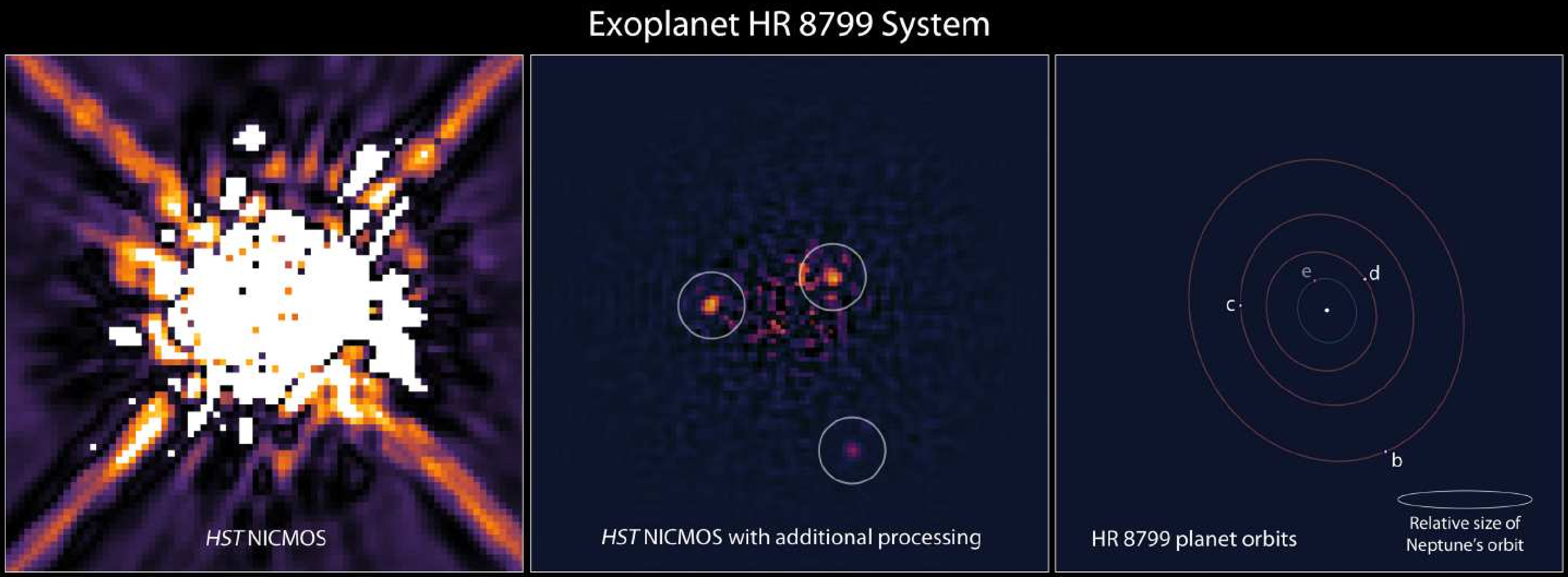
30 Doradus: Giant young star-cluster in Large Magellanic Cloud (150,000 ly), triggering birth of Sun-like stars (and surrounding debris disks).


Pillar and Stellar Jet in the Carina Nebula
HST WFC3/UVIS
F673N [S II]
F656N Hα
F502N [O III]
2 light-years
0.61 pasec
55″
N
E
HST WFC3/IR
F164N [Fe II]
F126N [Fe II]



HST/ACS Coronagraph imaging of planetary debris disk around Fomalhaut: First direct imaging of a moving planet forming around a nearby star!

JWST can find such planets much closer in for much farther stars.



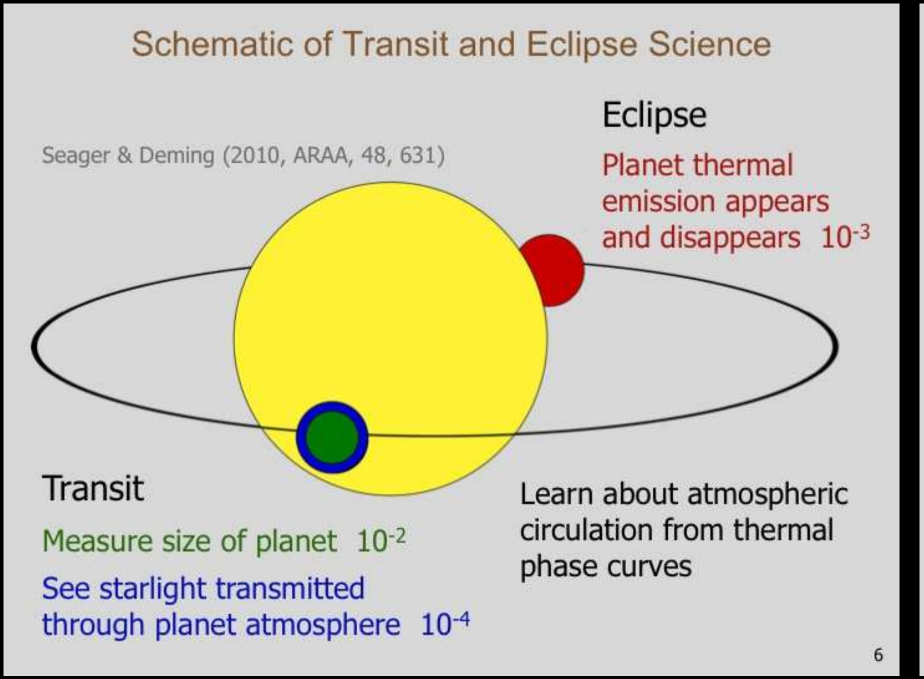
NASA, ESA, and R. Soummer (STScI)

STScI-PRC11-29

HST/NICMOS imaging of planetary system around the (carefully subtracted) star HR 8799: Direct imaging of planets around a nearby star.

Press release: http://hubblesite.org/newscenter/archive/releases/2011/29/

JWST can find such planets much closer in for much farther-away stars.



Schematic of Transit and Eclipse Science

Seager & Deming (2010, ARAA, 48, 631)

Eclipse

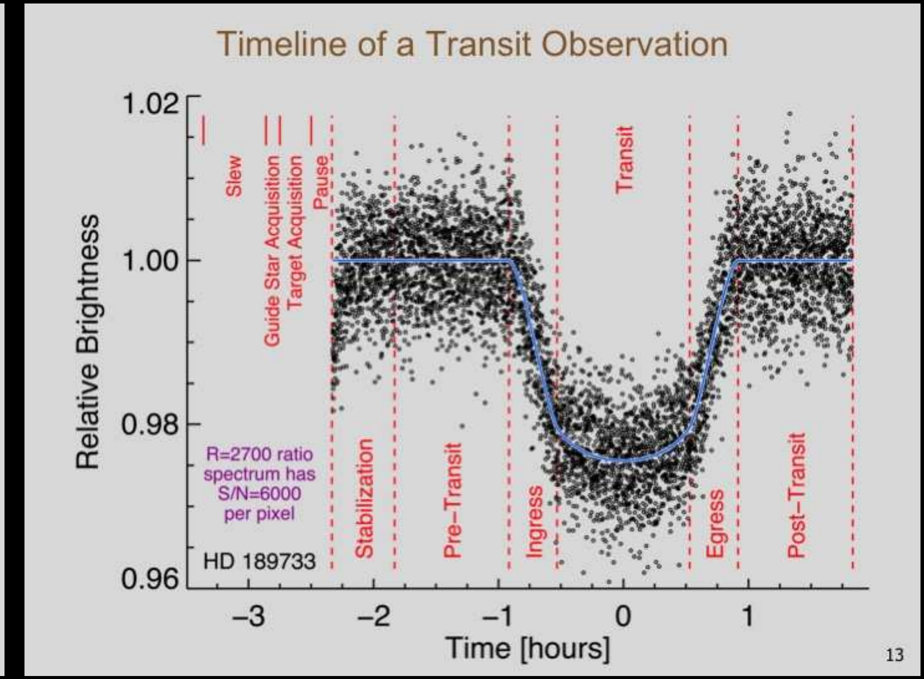
Planet thermal emission appears and disappears 10^{-3}

Transit

Measure size of planet 10^{-2}

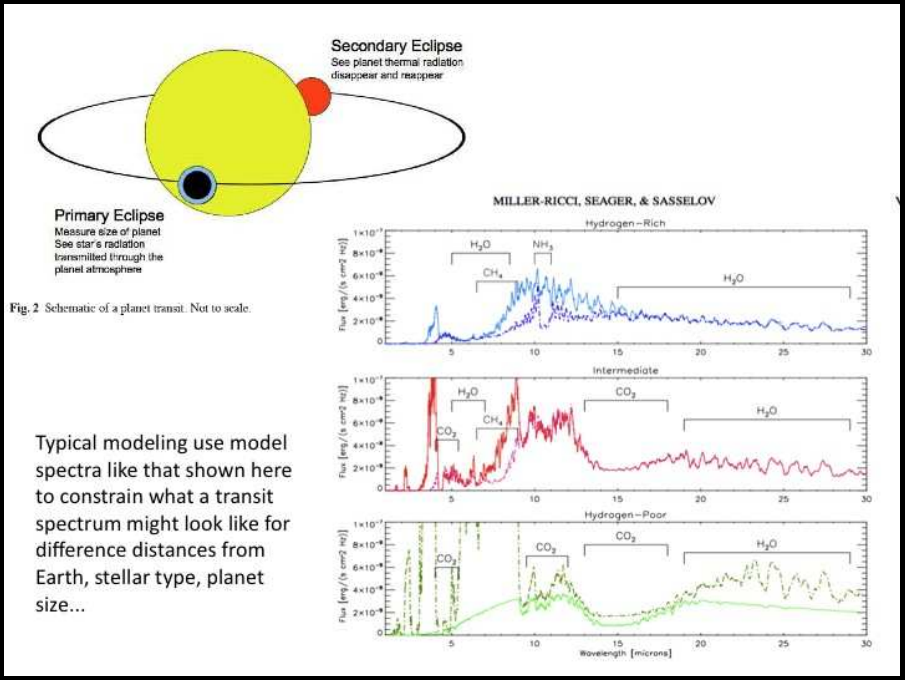
See starlight transmitted through planet atmosphere 10^{-4}

Learn about atmospheric circulation from thermal phase curves



Timeline of a Transit Observation

JWST can do very precise photometry of transiting Earth-like exoplanets.



Secondary Eclipse

See planet thermal radiation disappear and reappear

Primary Eclipse

Measure size of planet
See star's radiation transmitted through the planet atmosphere

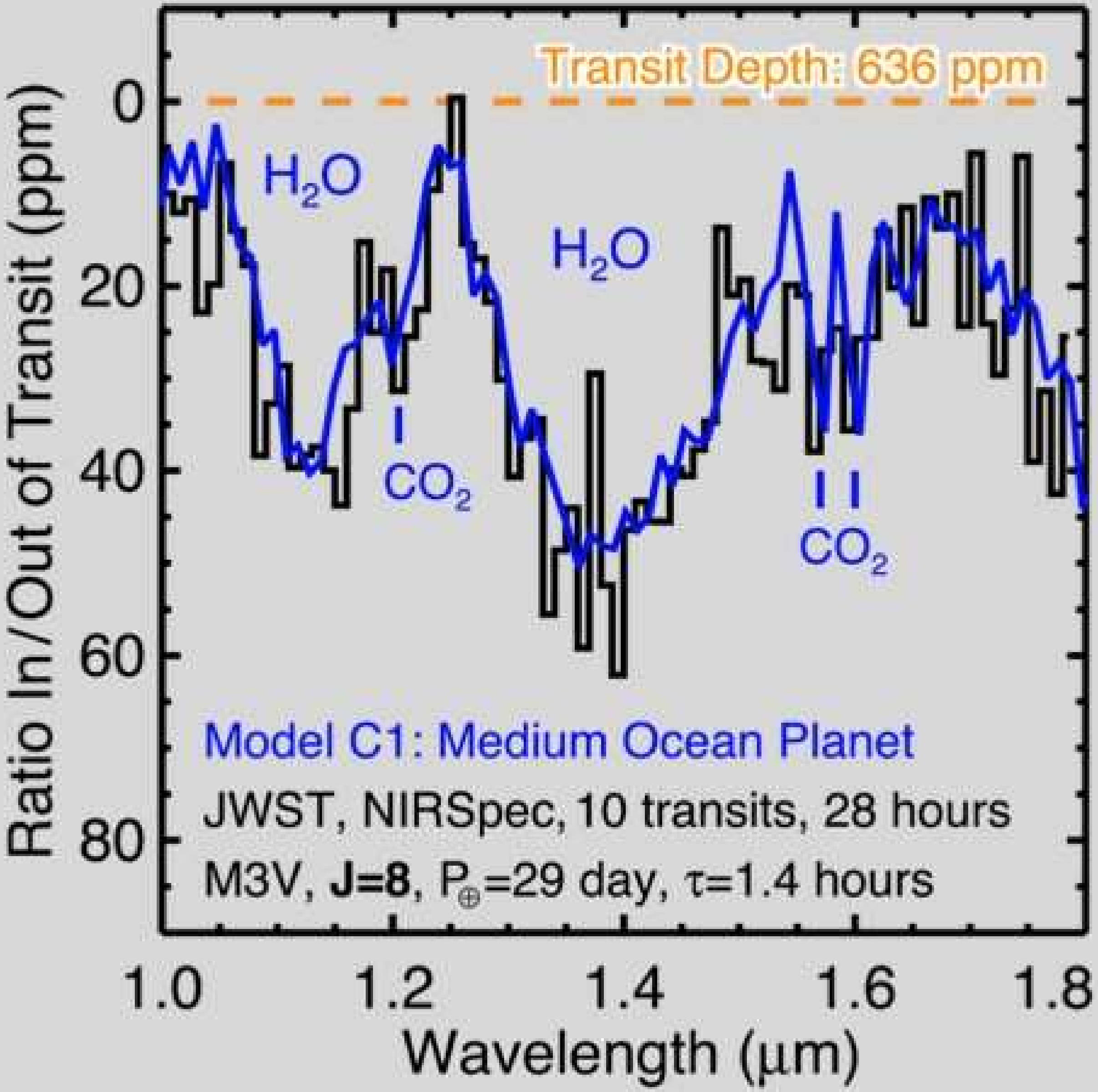
Fig. 2 Schematic of a planet transit. Not to scale.

MILLER-RICCI, SEAGER, & SASSELOV

Typical modeling use model spectra like that shown here to constrain what a transit spectrum might look like for difference distances from Earth, stellar type, planet size...

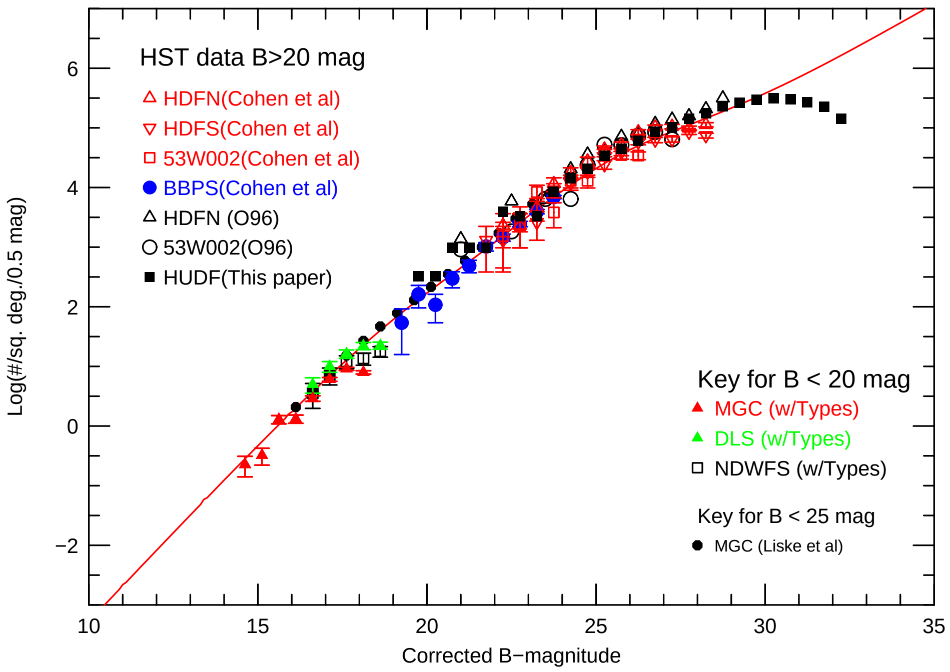
JWST IR spectra can find water and CO_2 in (super-)Earth-like exoplanets.

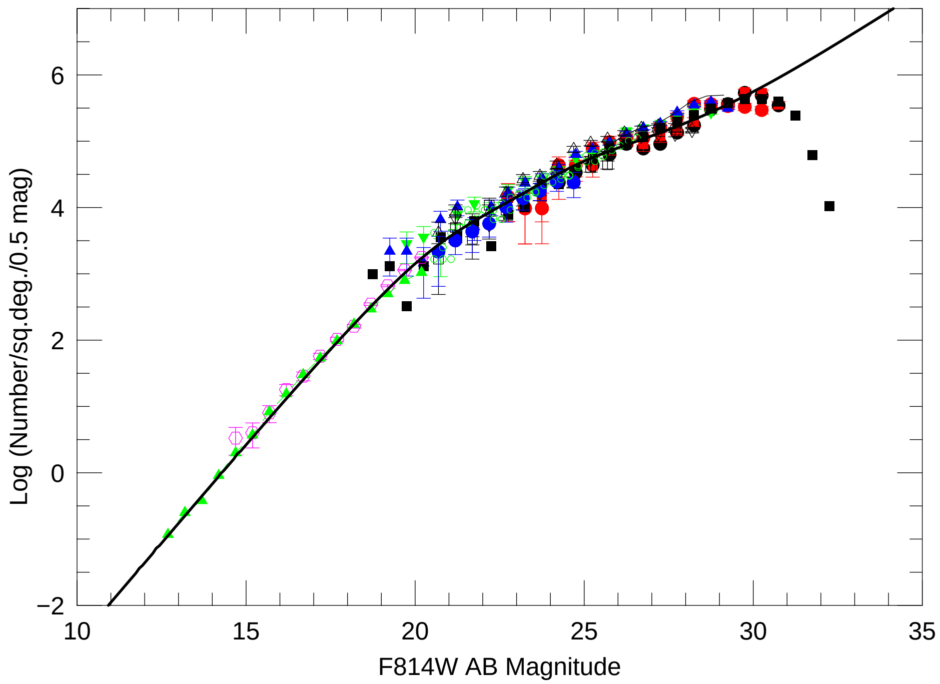
Transit Spectrum of Habitable "Ocean Planet"



JWST IR spectra can find water and CO_2 in transiting Earth-like exoplanets.

Appendix 1: Will JWST (& SKA) reach the Natural Confusion Limit?



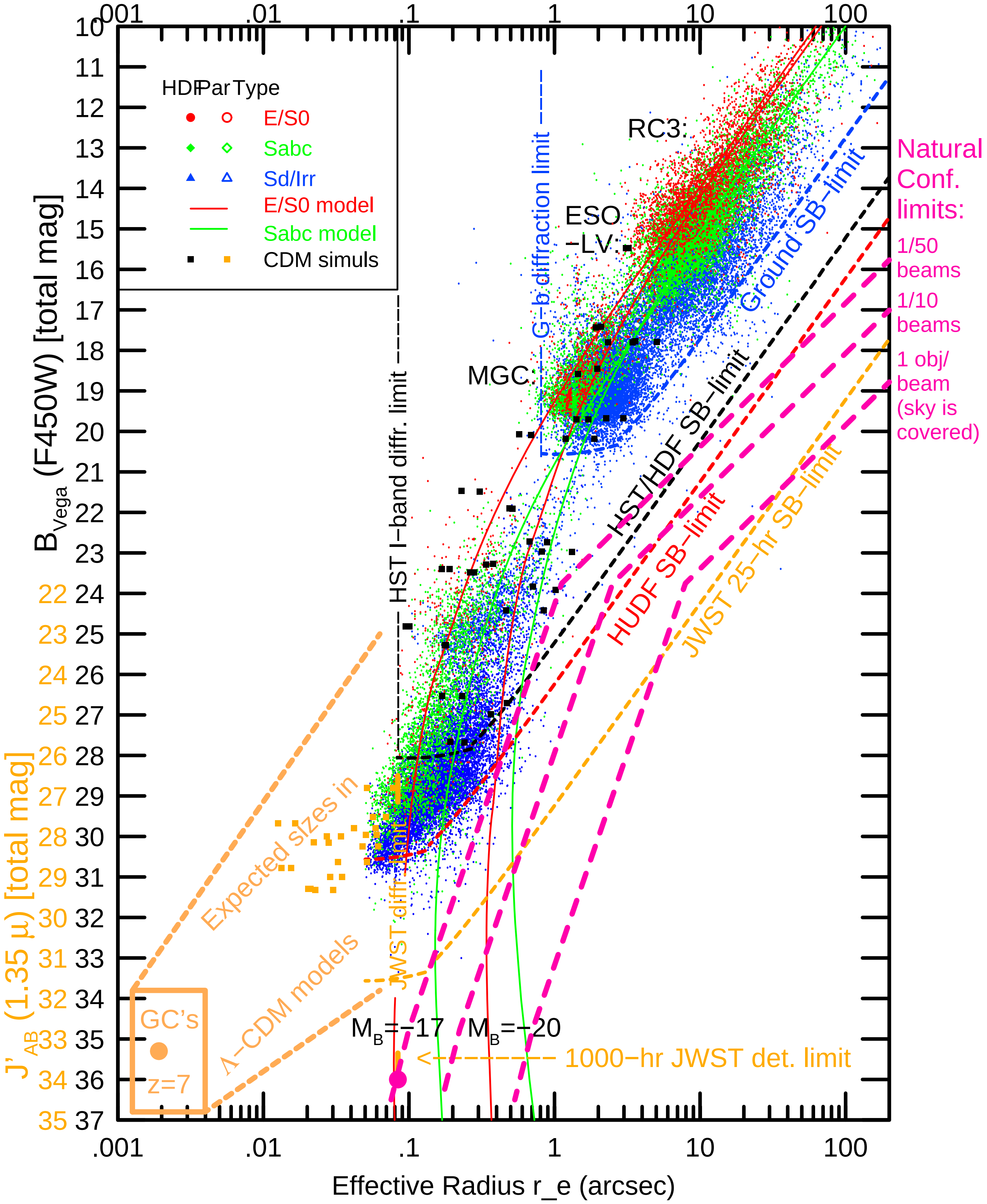


- ● HUDF galaxy counts (Cohen et al. 2006): expect an integral of $\gtrsim 2\times10^6$ galaxies/deg^2 to AB=31.5 mag ($\simeq$ 1 nJy at optical wavelengths). JWST and SKA will see similar surface densities to $\simeq$1 and 10 nJy, resp.

- ● $\Rightarrow$ Must carry out JWST and SKA nJy-surveys with sufficient spatial resolution to avoid object confusion (from HST: this means FWHM$\lesssim$0″.08).

- ● $\Rightarrow$ Observe with JWST/NIRSpec/MSA and SKA HI line channels, to disentangle overlapping continuum sources in redshifts space.

The natural confusion limit slowly sets in for AB≲25.



Combination of ground-based and space-based HST surveys show:

- (1) Apparent galaxy sizes decline from the RC3 to the HUDF limits:

- (2) At the HDF/HUDF limits, this is *not* only due to SB-selection effects (cosmological $(1+z)^4$-dimming), but also due to:

- (2a) hierarchical formation causing size evolution:
  $r_{hl}(z) \propto r_{hl}(0)\ (1+z)^{-1}$

- (2b) increasing inability of object detection algorithms to deblend galaxies at faint mags ("natural" confusion $\neq$ "instrumental" confusion).

- (3) At AB$\gtrsim$30 mag, JWST and at $\gtrsim$10 nJy, SKA will see more than 2×10^6 galaxies/deg^2. Most of these will be unresolved ($r_{hl} \lesssim 0\farcs1$ FWHM (Kawata et al. 2006). Since $z_{med}\simeq$1.5, this influences the balance of how $(1+z)^4$-dimming & object overlap affects the catalog completeness.

- For details, see Windhorst, R. A., et al. 2008, Advances in Space Research, Vol. 41, 1965, (astro-ph/0703171) "High Resolution Science with High Redshift Galaxies"